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Forest Vegetation Removal and Slope Stability in the Idaho Batholith

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RESEARCH SUMMARY

A study was conducted on two small watersheds in the Boise National Forest to determine the role of forest vegetation in maintaining more secure slopes in shallow, coarse-textured soils typical of the Idaho batholith. Both soil water piezometry and soil shear strength measurements were made in the watersheds.

Results of the field studies and supporting analyses indicate that forest vegetation often provides a critical margin of safety. Woody vegetation growing on slopes of the batholith contributes to stability by root reinforcement, by soil moisture depletion from interception and transpiration, by regulation of snow accumulation and melt rates, and by soil arching restraint between tree stems. Conversely, removal of vegetation from a slope by timber harvesting or wildfire results in a loss or reduction of effectiveness of these stabilizing mechanisms. Loss of vegetative stabilization in turn can lead to increased frequency of landslides as documented in this study.

Management implications of the study are discussed. Suggested measures and approaches include more stringent controls on size and location of clearcut units, greater use of "vegetation leave areas" or buffer zones particularly along haul roads and next to streams, and construction of hydraulic structures that divert water away from critical areas.

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INTRODUCTION

Slope Stability Problems in the Batholith

DESCRIPTION OF THE BATHOLITH

The Idaho batholith is a 16,000 mile^2 (41 000 km^2) mountainous area of granitic rocks located in central Idaho (see location map in fig. 1). Shallow, coarse-textured soils (loamy sands to sandy loams) typically develop on slopes that average 60 percent or more in many drainages. Soils of this type have been shown to be extremely erodible (Anderson 1954; André and Anderson 1961).

The granitic bedrock exhibits various degrees of weathering and fracturing. An idealized subsurface profile in a slope in the natural, undisturbed state, is shown in figure 2. The soil profile can be divided roughly into three major zones according to degree of weathering, indicated by surface soil (decomposed granitics and organic matter), fractured, disintegrated rock, and relatively competent, partly weathered bedrock. These zones vary in thickness, and changes in composition or texture are transitional rather than abrupt. A more precise delineation can be made by using a classification for granitic rocks developed by Clayton and Arnold (1972). Their classification criteria include apparent degree of mineral alteration and rock competency with respect to angularity of joint sets and response to a hammer blow.

The surface soil is almost without stones and is derived from granitic rock in a fairly advanced state of physical, if not chemical, weathering. This horizon usually consists of a sandy, coarse-textured soil with little or no intrinsic cohesion. In general it would be classified as an A-1-b soil under the American Association of State Highway Transportation Officials (AASHTO) Classification and as a SW-SM soil under the Unified Classification (Gonsior and Gardner 1971). Such relict features or vestiges of the original rock structure, as joint planes may persist in the soil. It is this part of the profile that is generally the most prone or vulnerable to both surficial and mass erosion (Durgin 1977).

Cyclonic storms and/or deep snowpacks that release large volumes of water to the soil within short periods are annual occurrences in the batholith region. Water supplied by these climatic events rapidly infiltrates the soil surface and continues downward until it reaches the zones of reduced hydraulic conductivity at the interface with the fractured, disintegrated bedrock. Continued inflow of water creates a saturated layer at this level, which in turn causes both buildup of a piezometric head and subsurface flow along the weathered bedrock surface (Megahan 1972). The subsurface flow zone is shown on figure 2. Depth of the soil piezometric surface is one of the most important factors influencing stability of steep mountain slopes mantled with shallow, noncohesive soils.

Figure 1. — Location map showing the Idaho batholith and study area.

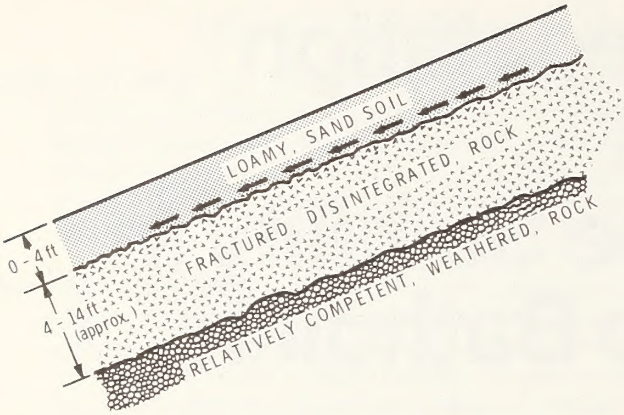

Figure 2. — Typical soil profile and slope geometry in the Idaho batholith (excluding swales, depressions, and other topographic lows). Arrows indicate the shallow subsurface flow zone.

DOCUMENTATION OF SLOPE FAILURES

The Idaho batholith area contains valuable timber reserves as well as other resources important to the regional and national economies. This has led to considerable development activity, particularly road construction and timber harvesting. The batholith is also a critical area with respect to surface and subsurface stability. Surface erosion and landslides are prevalent. Consequently, much of this development activity has increased the occurrence of landslides and provided large exposed areas from which sediment can readily be removed by surface erosion processes (Megahan and Kidd 1972).

Slope stability problems in the batholith have been studied and documented by a number of investigators in the past decade (Croft and Adams 1950; Gonsior and Gardner 1971; Megahan and Kidd 1972; and Megahan and others 1978). An inventory and analysis by Megahan and others (1978) of some 1,400 landslides on two National Forests reveals some interesting findings about the nature and cause of these slope failures.

The survey was carried out on the Clearwater and Boise National Forests and represents geologic conditions found in the western and central portions of the Northern Rocky Mountain physiographic province. Most of the area surveyed in the landslide inventory falls within the Idaho batholith. Portions of the Clearwater National Forest, however, are outside the batholith. Here, low grade metasediments (mostly quartzite) of the Belt Series predominate.

Almost three quarters (72 percent) of the slides inventoried were debris avalanches or debris slides. For a 3-year study period, a total of almost 15 acres (6 hectares) of forest land were lost to landslides each year on the Clearwater National Forest alone. Repair costs to simply clear debris from roads and replace road fill material averaged $56,000 per year. An average of 56,000 cubic yards/year (43 000 cubic meters/year) of slide material was delivered to active stream channels with adverse impacts on the fisheries resources of the region.

By far the most likely cause of accelerated landslide activity was road construction. Roads alone accounted for 58 percent of the landslides inventoried. In combination with logging and/or forest fires, roads accounted for a total of 88 percent of all landslides. Vegetation removal alone accounted for 9 percent of the landslide activity. Only 3 percent of the landslides occurred on "natural" or undisturbed slopes. These relationships are shown graphically in figure 3.

The Idaho batholith is not unique with regard to its high incidence of slope failures. Numerous slides have occurred in granitic areas all around the world (Durgin 1977; Jones 1973). Granitic masses or batholiths commonly form the core of mountains that may have extreme topographic relief. Progressive physical, chemical, and biological weathering weakens the granitic rocks and make them susceptible to erosion and mass movement (Clayton and others 1979). Natural events such as intense rainstorms, earthquakes, or other perturbations can then trigger slides at susceptible sites. Developmental activity such as road construction and timber harvesting can accelerate or intensify this process.

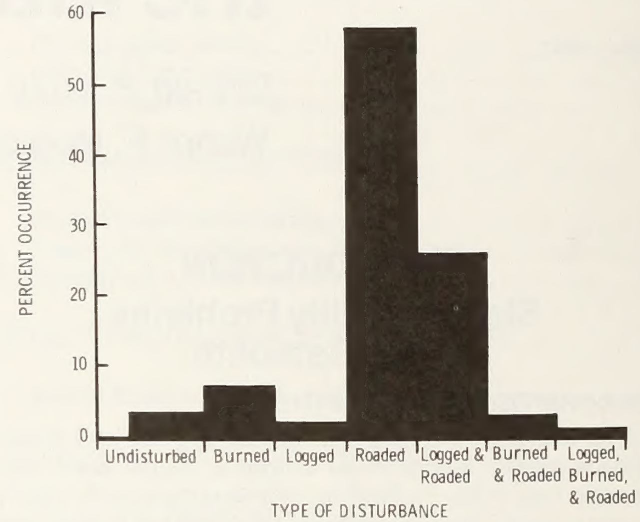

Figure 3. — Landslide occurrence by type of disturbance, western and central Northern Rocky Mountain physiographic province (from Megahan and others 1978).

Potential Effects of Timber Removal

STABILIZING INFLUENCE OF WOODY VEGETATION

Central to the purpose of this paper is the role of forest vegetation in maintaining more secure slopes. This question has been analyzed in considerable detail by Gray (1970, 1978), who identified four principal mechanisms by which forest vegetation enhances stability, namely:

(a) Mechanical reinforcement from the root system.
(b) Regulation of soil moisture content and piezometric levels through transpiration, interception, and by affecting snow accumulation and rate of melting.
(c) Buttressing or soil arching action between the trunks or stems.
(d) Surcharging from the weight of trees.

The effectiveness of these hydromechanical influences depends upon soil and slope conditions at particular sites. Root reinforcement and buttressing, for example, would be of little avail in arresting deep-seated, rotational failures in cohesive soils. On the other hand, in shallow, coarse-textured soils which are prone to debris sliding and avalanching along an inclined bedrock surface, the situation is quite different; root reinforcement and buttressing may contribute significantly to stability in this case. Dramatic examples of such slope stabilization by ponderosa pines are shown in figures 4 and 5. The importance of these "hydromechanical" contributions of forest vegetation to the stability of slopes in the Idaho batholith is examined in greater detail later in the paper.

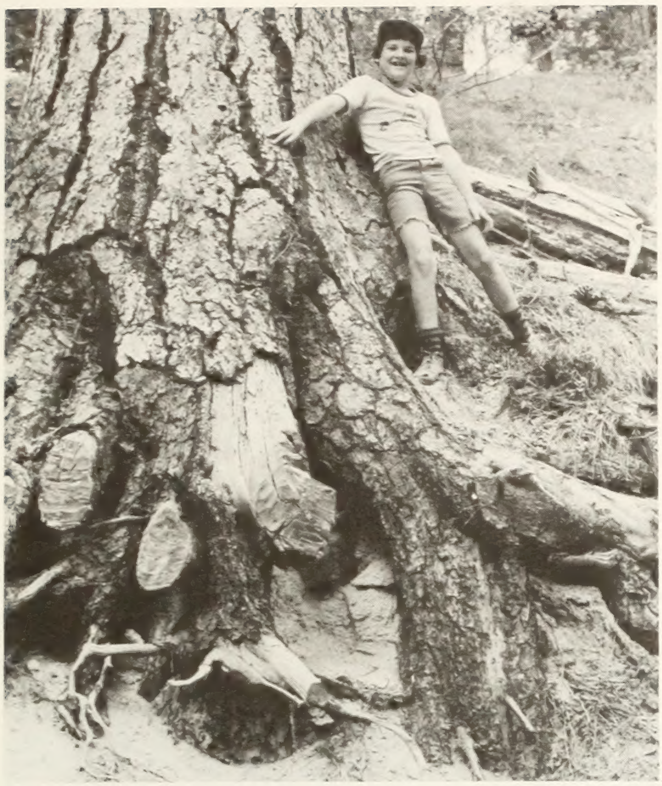

Figure 4. — Ponderosa pine tree (*Pinus ponderosa* Laws) buttressing and restraining a slope in a road cut in granitic soil of the Idaho batholith. Note massive buttress roots in right foreground.

Figure 5. — Slope buttressing by ponderosa pine. Unbuttressed part of slope on left has failed. Mendocino National Forest, California.

CONSEQUENCES OF REMOVAL

One way of ascertaining the significance or contribution of forest vegetation to the stability of slopes is to examine the consequences of its removal. The concensus of investigators on this question is clear, namely, indiscriminate removal weakens soils and destabilizes slopes. This concensus applies not only to the Idaho batholith but to other forested slopes as well (Bishop and Stevens 1964; Rice and Krammes 1970; Swanston 1974; Swanson and Dyrness 1975; O'Loughlin 1974; Swanston and Swanson 1976; and Wu 1976).

The landslide inventory conducted by Megahan and others (1978) in the Boise and Clearwater National Forests revealed significant contributions of vegetation roots to stability of steep mountain slopes. Landslide hazard was observed to increase in direct proportion to the amount of vegetation removed because of root decay. The amount of residual vegetation, including both trees and shrubs, was an important factor regulating the increase in landslide hazards following timber cutting or forest fire. The rate of root decay relative to the rate of new root growth appeared to determine the time of occurrence of maximum landslide hazard following vegetation removal. On the average, landslide hazards were greatest 4 years after timber removal and remained high for about 6 years. By the end of 20 years, landslide hazards had returned to their predisturbance levels. These slide-vegetation relationships are shown graphically in figures 6 and 7.

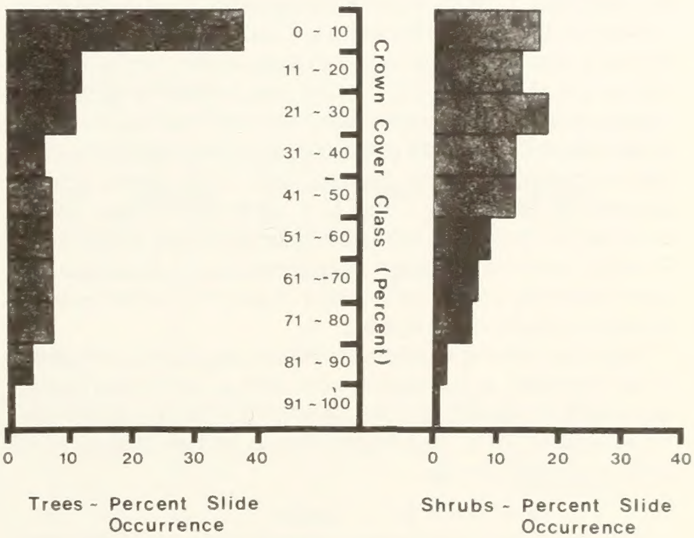

Figure 6. — Landslide occurrence by vegetation crown cover, western and central Northern Rocky Mountain province (from Megahan and others 1978).

Figure 7. — Landslide occurrence by years since logging, western and central Northern Rocky Mountain province (from Megahan and others 1978).

DESCRIPTION OF PINE CREEK STUDY

The Pine Creek study was established originally to evaluate subsurface flow occurrence on representative granitic slopes and the effect of clearcutting and road construction on subsurface flow emerging on the face of road cut slopes.

Physiographic Setting

The Pine Creek drainage is a tributary to the Middle Fork of the Payette River above Crouch, Idaho. The study was installed on two small undisturbed watersheds of 2.4 and 0.8 acres (1.0 and 0.3 hectares). These microwatersheds are representative of first order drainages found in midelevation, fluvial landscapes of the Idaho batholith.

Slope gradients on the two study watersheds range from 35 to more than 70 percent and aspects range from northeast to northwest (see fig. 8). The soil is a Koppes loamy coarse sand and is a member of the sandy-skeletal mixed family of typic cryoborolls (Nelson 1976). Sandy loam to loamy sand soils overlie moderately weathered and fractured bedrock and range in depth from 6 inches (15 cm) on ridges to about 48 inches (122 cm) in drainage bottoms. Surface soils were almost entirely covered by litter up to 1 inch (2.5 centimeters) deep before disturbance. Soils are poorly developed, exhibiting only shallow A and C horizons. Average physiographic and soils data are summarized by watershed in table 1. A general view of the study watershed is shown in figure 9.

Vegetation on the watersheds before disturbance consisted of an overstory of ponderosa pine (*Pinus ponderosa* Laws.), Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), and Engelmann spruce (*Picea engelmannii* Parry), and an understory of small trees and shrubs.

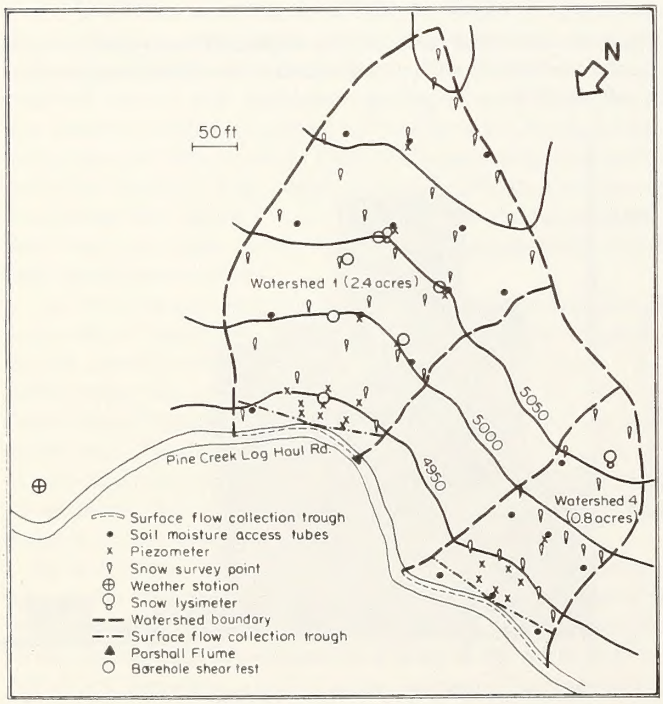

Figure 8. — Pine Creek study area showing location of instrument and data collection stations in the watersheds.

Annual precipitation in the vicinity averages approximately 32 inches (81 cm). A large portion occurs as snowfalls; consequently, a large snowpack accumulates often to a total depth in excess of 60 inches (152 cm), or 20 inches (51 cm) of water equivalent. During the spring, the snowpack melts in a relatively short time, contributing large volumes of water to the soil that generate subsurface flow and measurable piezometric heads.

Table 1. — Descriptive data for Pine Creek study watersheds, Boise National Forest

Watershed	Average slope	Average soil depth	Average elevation	Average aspect (azimuth)	Average crown cover
	Percent	*Inches*	*Feet*	*Degrees*	*Percent*
Watershed No. 1 (clearcut)	52	32	5,050	337 NNW	63
Watershed No. 4 (uncut)	62	30	5,005	335 N	43

Figure 9. — View of Pine Creek study area, Watershed No. 1, Boise National Forest, Idaho. Arrows point to slope failures. (Photo taken July 1977.)

History of Land Use

The study was initiated in 1969 and proceeded on schedule until November 1972 when the larger watershed (No. 1) was clearcut. A total of 36 ponderosa pines, averaging 25.8 inches (65.5 cm) in diameter, and 126 Douglas-fir, averaging 13.4 inches (34.0 cm) in diameter, were removed as a result of the logging. The total volume of timber removal averaged 14,500 board feet per acre (203 m^3/ha). Slash treatment included lopping, scattering, and some hand piling. On August 20, 1973, a wildfire swept through the Pine Creek drainage, including the two study areas. This unplanned event compromised some of the hydrologic studies, but also provided an opportunity to compare the postburn response of a cutover and adjacent undisturbed watershed.

Postfire Stability Problems

Following the wildfire, it was apparent that accelerated surface soil erosion (by rilling and rain splash) was occurring on the clearcut watershed. This was corroborated by studies conducted by Megahan and Molitor (1975). The erosion was entirely postfire; there was no evidence of surface erosion on the clearcut watershed before the fire. The clearcutting had a twofold effect: it removed protective canopy cover (an important source of postfire litter); and it increased surface fuel loading that led to a more intense burn on the clearcut watershed.

Mass erosion also occurred in 1974 and 1975 after the fire. It was manifested by progressive failures of cut slopes above the haul road that traversed the two watersheds (see fig. 9). Other landslides also occurred within the 2,200-acre (890-ha) Pine Creek burn (table 2). It is interesting that only 50 percent of these slides were road associated (most were rotational slumps in road cuts). The remainder were shallow, debris slides or flows with an average depth of 26 inches (66 cm). These slides occurred on natural slopes with an average gradient of 73 percent (36 degrees). Typical examples of both erosion and slope stability problems in the study watersheds are shown in figures 10 and 11.

Table 2. — Landslide study on the Boise National Forest (1975)

		Slides in the Pine Creek Burn						
Slide identification number	Slide type	Length	Width	Depth	Volume	Gradient	Soil depth	Cause
		Feet			*Cubic yard*	*Percent*	*Inches*	
BO-613-75	Debris slide	24	37	3	50	60	12	Road cut
BO-614-75	Debris slide	12	15	1.5	7-10	60-70	Missing	Not road associated
BO-615-75	Debris slide or flow	Missing	Missing	Missing	9	Missing	Missing	Road cut
BO-616-75	Debris flow(?)	15	15	6	10-12	75	18	Road cut
BO-617-75	Debris torrent/flow	200	10	1	200	65	16	Not road associated
BO-618-75	Debris avalanche	20	10	3	40	Missing	Fill failure	Road fill (culvert)
BO-619-75	Rotational slump	15	30	1	60	100	22	Road cut
BO-620-75	Rotational slump	35	57	1	220	80	Missing	Road cut
BO-621-75	Rotational slump and debris slide	30	110	2	350	70	14	Road cut
BO-622-75	Rotational slump	7	45	1	30	70	35	Road cut
BO-623-75	Debris avalanche	62	10	1	160	173	Missing	Not road associated
BO-624-75	Rotational slump	54	11	2	150	80	Missing	Road cut
BO-625-75	Debris flow	150	20	2.5	550	80	15	Not road associated
BO-626-75	Debris flow	75	30	2	240	85	23	Not road associated
BO-627-75	Debris flow	25	8	3	30	70	16	Not road associated
BO-628-75	Debris flow	90	10	2	140	70	15	Not road associated
BO-629-75	Debris flow	40	17	2	55	80	30	Not road associated
BO-630-75	Debris flow	65	22	2	125	70	16	Not road associated

Figure 10. — Slipout in slope above road cut, Watershed No. 1, Pine Creek study area, Boise National Forest, Idaho. (Photo taken July 1977.)

Figure 11. — Large gully in slope, Watershed No. 1, Pine Creek study area, Boise National Forest, Idaho. Gully was formed by subsurface flow emerging at cut face followed by piping and "spring sapping," which triggered localized slope failure. (Photo taken July 1977.)

STUDY DESIGN AND METHODS

Overall Experimental Design

As noted previously, the original purpose of the Pine Creek study was to evaluate subsurface flow occurrence on representative granitic slopes and the effect of clearcutting and road construction on subsurface flow. Hydrologic data collection on the study watersheds included water inflow, change in water storage, and outflow of water occurring as subsurface flow.

Subsurface flow was measured with collection troughs installed on the road at the base of the cut slope across the entire width of the watersheds. Estimates of water inflow into the watersheds and changes in water storage were obtained from a recording rain gage and snow lysimeter. In addition, 45 snow stakes and 23 neutron access tubes for soil moisture determination were located in a grid pattern on the study watersheds. Finally, 25 piezometers were located in suspected water-accumulation areas within the watersheds. All data collection sites or stations are shown in figure 8.

Some additional data were collected following the wildfire on the study area to evaluate the effects of burning on surface erosion rates. Data compilation included rill surveys, a network of erosion pins, and collection of eroded material in splash pans and in the subsurface flow collection troughs.

Piezometric levels or ground water conditions are also critical determinants of the mass stability of slopes. Accordingly, a conjunctive slope stability investigation was undertaken in the experimental watersheds in the summer of 1977. Estimates of soil shear strength (required for stability analyses) were obtained from in-situ borehole shear tests (see fig. 8 for locations) and from results of laboratory triaxial tests on granitic soils reported by other investigators (Lumb 1962; Gonsior and Gardner 1971; Hampton and others 1974[1]; Prellwitz 1975; USDA Forest Service 1977). The slope stability investigation also included an analysis of the contribution of forest vegetation to slope stability from root reinforcement, surcharging, and buttressing or soil arching action.

Piezometer Installation and Data Collection

A total of 25 piezometers were installed in the study watersheds: 14 in Watershed No. 1 and 11 in Watershed No. 4. The precise location of these piezometers is shown in figures 12 and 13. It should be noted that piezometer Nos. 10-14 and 9-11 in Watersheds 1 and 4, respectively, were lost in slope failures that occurred in 1974 and 1975 (see figs. 12 and 13 for location).

The piezometers were installed vertically by hand augering a 2-inch (5-cm) hole through the loamy sand soil to the surface of the underlying fractured, disintegrated rock. A typical piezometer installation is illustrated schematically in figure 14. The piezometers were read frequently during the active snowmelt period in late spring and at monthly intervals throughout the following summer and fall. Both the present and the maximum water depths were measured at each piezometer. The maximum reading between measurements was determined by noting the position of powdered cork on the aluminum rod. The powdered cork floats up as piezometric levels rise and adheres to the aluminum rod at the point of highest rise. This technique was employed by Swanston (1967) in his study of soil water piezometry in southeast Alaska.

[1]Hampton, D., W. F. Megahan, and J. L. Clayton. 1974. Soil and rock properties research in the Idaho batholith. USDA For. Sci. Lab. Rep., Boise, Idaho 121 p.

Figure 12. — Location of piezometers and limits of slide zone, Watershed No. 1, Pine Creek study area.

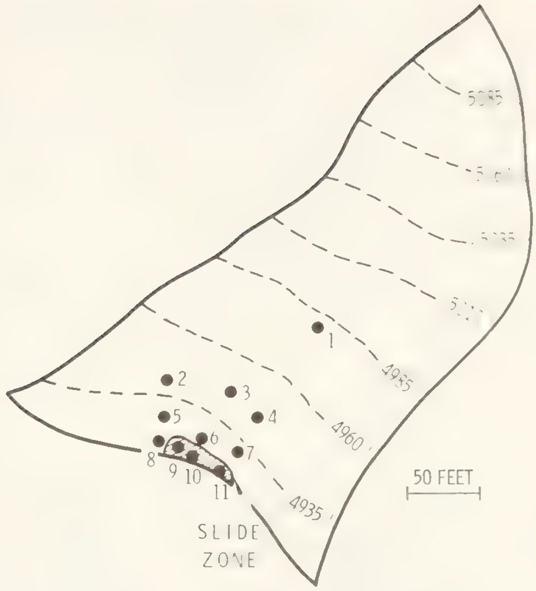

Figure 13. — Location of piezometers and limits of slide zone, Watershed No. 4, Pine Creek study area.

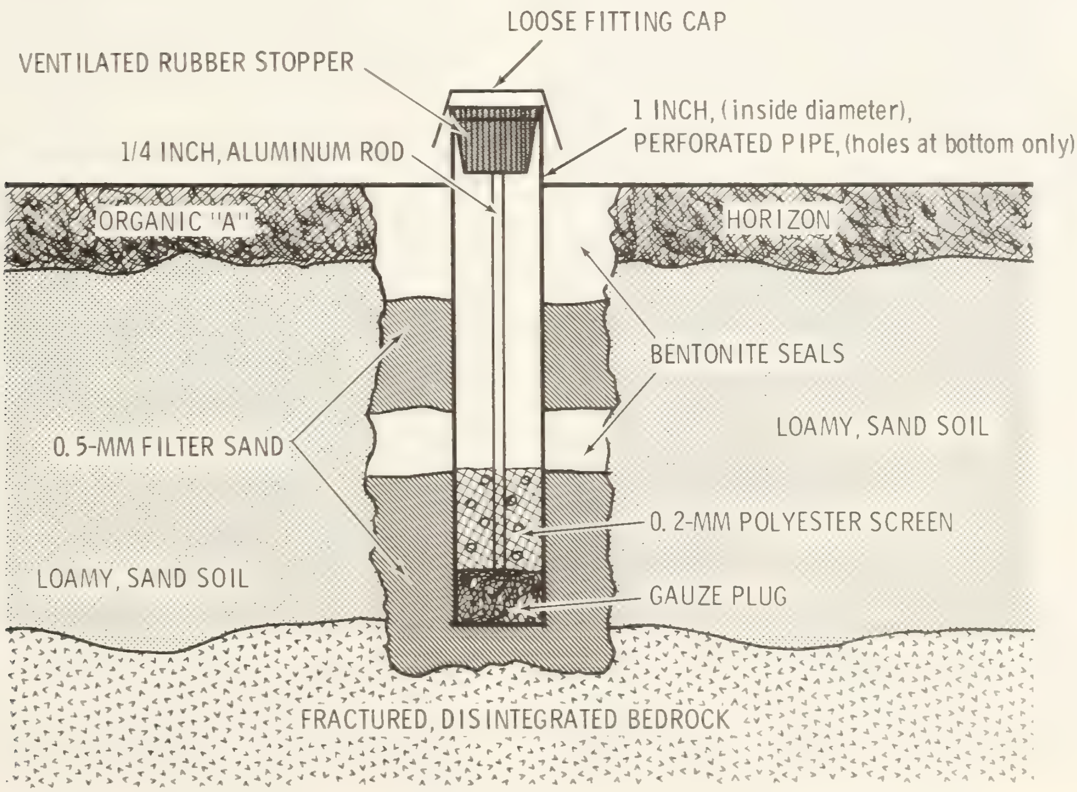

Figure 14. — Schematic illustration of typical piezometer installation, Pine Creek study area.

Slope Stability Data Collection

IN-SITU BOREHOLE SHEAR TESTS

The borehole, direct shear test is a rapid method for obtaining in-situ shear strength parameters. Borehole shear tests avoid the need for recovering samples with all the attendant problems of sample disturbance and representative sampling (Handy and Fox 1967; Wineland 1975).

The method basically consists of lowering a shear head down a 3-inch (8-cm) diameter borehole to a desired depth in the soil profile (fig. 15), expanding the shear head against the sides of borehole with a known normal stress, and then recording the maximum shear stress required to crank the shear head up the hole (fig. 16). The test can be run at several depths in the borehole to provide an idea of how the soil shear strength parameters vary with depth.

The boreholes were drilled to the bottom of the soil horizon or disintegrated rock interface (fig. 2) using a 2-inch (5-cm) bucket auger. The holes were then widened to 3 inches (8 cm) in diameter using a thin-walled reamer. Occasionally undisturbed samples were taken with the reamer for density and moisture content determinations. These samples were also analyzed for their grain size distribution.

Figure 15. — Expandable shearing head of borehole device prepared for lowering down borehole.

Figure 16. — Borehole, direct shear test in progress in shallow, coarse-textured soil developed on granitic rocks of the Idaho batholith. Pine Creek study area, Boise National Forest.

ROOT DISTRIBUTION AND STRENGTH TESTS

In order to make an assessment of the rooting contribution to soil shear strength and slope stability, it was necessary to obtain an estimate of both root distribution and root strength in the granitic soil of the study watersheds. This estimate was obtained from results of studies in granitic soils of other watersheds in the Idaho batholith (Curtis 1964; Burroughs and Thomas 1977; and Megahan and others 1978).

Burroughs and Thomas (1977) measured the concentration of intermingled lateral roots (Douglas-fir) in a vertical plane or trench midway between trees. Inclusion of all intermingled, fresh roots up to 0.4 inch (1 cm) in diameter leads to a calculated "root area ratio" of 0.045 percent. Most of the roots counted fell into this size class. Roots in the size class 0 to 0.4 inch (0 to 1 cm) comprised 96 percent of the roots counted in the sample area. On the other hand, inclusion of fresh roots up to 3 inches (8 cm) in diameter increased the root area ratio to 0.174 percent even though these larger roots were not numerous. Root area ratios less than 1 percent may not seem significant with regard to slope stability, but, as shown later, even a few tenths of a percent of root section in the soil is sufficient to provide a substantial and critical amount of shear strength increase in shallow, coarse-textured soils.

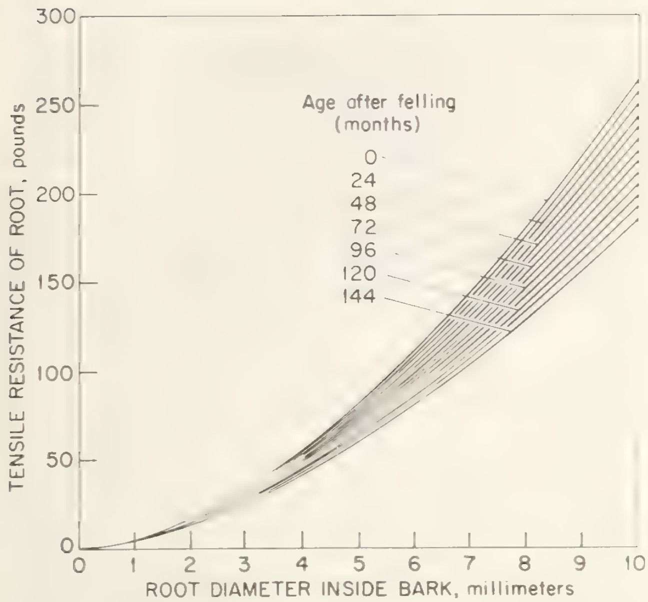

Figure 17. — Tensile resistance of roots of Rocky Mountain Douglas-fir as a function of age and size of root (from Burroughs and Thomas 1977).

Burroughs and Thomas (1977) also determined the tensile resistance of roots for various size classes and various elapsed times after cutting as shown in figure 17. Tensile resistance was only measured for Douglas-fir roots in the size interval 0 to 0.4 inch (0 to 1 cm). The tensile strength computed as tensile resistance divided by root cross sectional area (as distinct from resistance plotted in fig. 17) decreased from 3,280 lb/in^2 (22 600 kPa) for a 0.08-inch (2 mm) diameter root to 2,150 lb/in^2 (14 800 kPa) for a 0.4-inch (10 mm) root. The average tensile strength for roots in this size interval, that is, 0 to 0.4 inch (0 to 1 cm), was approximately 2,720 lb/in^2 (19 800 kPa). This variation in root tensile strength with root size has been observed by other investigators as well (Gray 1978; Wu 1976). This type of information makes it possible to compute the average tensile strength **per unit area of soil** for a Douglas-fir root-soil system. By using a simple root or fiber reinforcement model described in the next section, these data can in turn be translated into a shear strength increase or pseudo "root cohesion."

Unfortunately, Burroughs and Thomas (1977) only looked at the concentration of lateral roots. It is the vertical roots (tap and sinker roots) that will contribute most to sliding resistance of soils on steep, inclined slopes. Studies by Curtis (1964) on ponderosa pine indicate deep penetration of tap roots and sinker roots in a cylindrical zone around each tree in granitic soils of the batholith. The extent of vertical root penetration and concentration across the slope surface as a whole is not known precisely.

One way of estimating this concentration is simply to use root area ratios that can be calculated from root distributions measured by Burroughs and Thomas (1977). Those authors caution, however, that their measurements were restricted to lateral roots of Douglas-fir crossing a vertical plane midway between trees. On the other hand, they also state that the finer roots (0.4 inch [1 cm] and smaller) are found throughout the rooting zone of each tree root system. Furthermore, they note that these same roots "... will penetrate a shallow soil overlying a weathered or well-fractured bedrock or glacial till to anchor the soil-root mass."

More direct data on critical root distribution in granitic soils can be obtained from the landslide study by Megahan and others (1978). The size and frequency of roots exposed in a slide shear plane in a forested slope are summarized in figure 18. The dominant size class (modal value) of roots in the shear plane was 0.20 to 0.40 inches (0.51 to 1.02 cm) in diameter. The dominant (modal value) root density class was 6.5 to 10.5 roots per square foot (70 to 113 roots per square meter). This information yields root area ratios ranging from 0.14 to 0.93 percent using data from the modal class. Burroughs and Thomas (1977) found the same class to be dominant for Rocky Mountain Douglas-fir in their study, i.e., most of the roots they counted fell into the 0 to 0.4 inch (0 to 1 cm) size range.

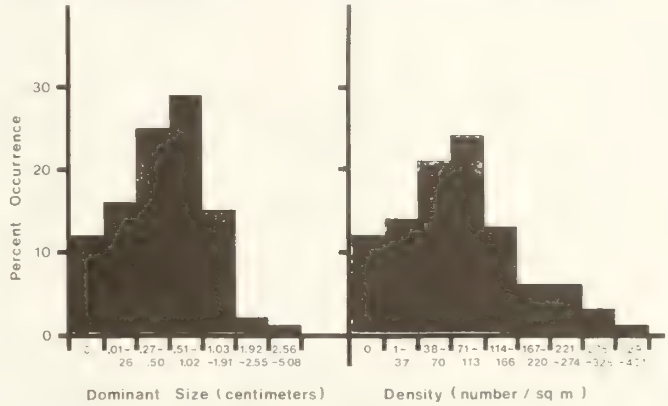

Figure 18. — Landslide occurrence by sheared roots at slide site (from Megahan and others 1978).

In contrast, the root area ratio (0.045 percent) calculated from their study for this size class was much lower than those computed from the data of Megahan and others (1978). The difference is most likely caused by the fact that Burroughs and Thomas (1977) counted only Douglas-fir roots in vertical planes midway between tree stumps, whereas in the other study all roots were counted in shear planes parallel to the slope, regardless of species. Wu (1976) measured root area ratios ranging from 0.05 to 0.17 and averaging 0.08 percent in his study of vegetative influence on landslide occurrence in Southeast Alaska. His root area ratios were measured at the contact between the B and C soil horizons, in soils developed on glacial till slopes supporting a spruce-hemlock forest.

Kozlowski (1971) observed that root structure as well as depth and rate of root growth are markedly influenced by the rooting medium or environment. The water-holding capacity or water availability in a soil is particularly important in this regard. Roots tend to avoid regions of high moisture stress and invade or permeate moist zones. In the case of shallow, coarse-textured soils of the Idaho batholith, the most favorable region for roots to exploit from a moisture standpoint is the zone close to the contact between the soil and the underlying fractured, disintegrated bedrock. In other words, one should expect a fairly high concentration of vertical or sinker roots across this contact.

This expectation is partly confirmed by McMinn (1963) in his extensive study of the characteristics of Douglas-fir root systems. Hydraulic excavation of root systems in Douglas-fir stands revealed a pronounced tendency towards steeply inclined or downward root penetration, not only from the central, deep root system, but also from semivertical roots (sinkers) from laterals. This trend was most pronounced in older tree stands.

From all the aforementioned studies, a root area ratio in the range of 0.05 to 0.15 percent can be considered a reasonable or preliminary lower bound estimate in a slope for purposes of stability calculations in forested, granitic slopes of the Idaho batholith. This topic will be considered further in a subsequent section dealing with root reinforcement and its contribution to slope stability.

TREE STEM SURVEY

Tree stem survey data from nearby experimental watersheds in the adjacent Silver Creek drainage were used for calculating slope surcharge from the weight of forest vegetation and for estimating buttressing or soil restraint from tree trunks firmly rooted to the underlying bedrock.

A stem count and inventory for five cutting units on two experimental watersheds in the Silver Creek drainage is summarized in table 3. The inventory included only stems 12 inches (30.5 cm) and over in diameter at breast height. Average tree spacings (S) were calculated assuming a simple cubic and triangular array. Average size of openings (B) between "vertical root cylinders" were calculated assuming the diameter of the root cyclinder (D_R) was approximately five times the stem or trunk diameter (D_T) at breast height. Field studies by Wu (1976) and Curtis (1964) indicate that this diameter ratio is reasonable. The various spacing relationships are illustrated schematically in figure 19.

Table 3. — Stem count and tree spacings for experimental watersheds, Silver Creek study area, Boise National Forest

Cutting unit	Total area	Total stem area	Number of stems 12 inches in diameter and over	Average stem diameter	Average stem[1] spacing	Estimated[2] root zone diameter	Estimated size of opening between root zones
	Acres	*Feet²*		*Feet*			
Control Creek No.3	96.6	2,690	960	1.89	66	9.4	57
4	51.5	3,503	1,567	1.69	38	8.4	30
5	19.5	1,635	778	1.64	33	8.2	25
6	21.1	2,215	880	1.79	32	8.9	23
K-1 Creek	36.7	1,731	620	1.88	51	9.4	41

[1]Based on simple, cubic array where spacing (S) = $\left[(\text{area cutting unit})/(\text{number stems} > 12 \text{ in.}) \right]^{1/2}$.
[2]Assume $D_R = 5D_T$ (estimate based on data in Curtis [1964] and Wu [1976]).

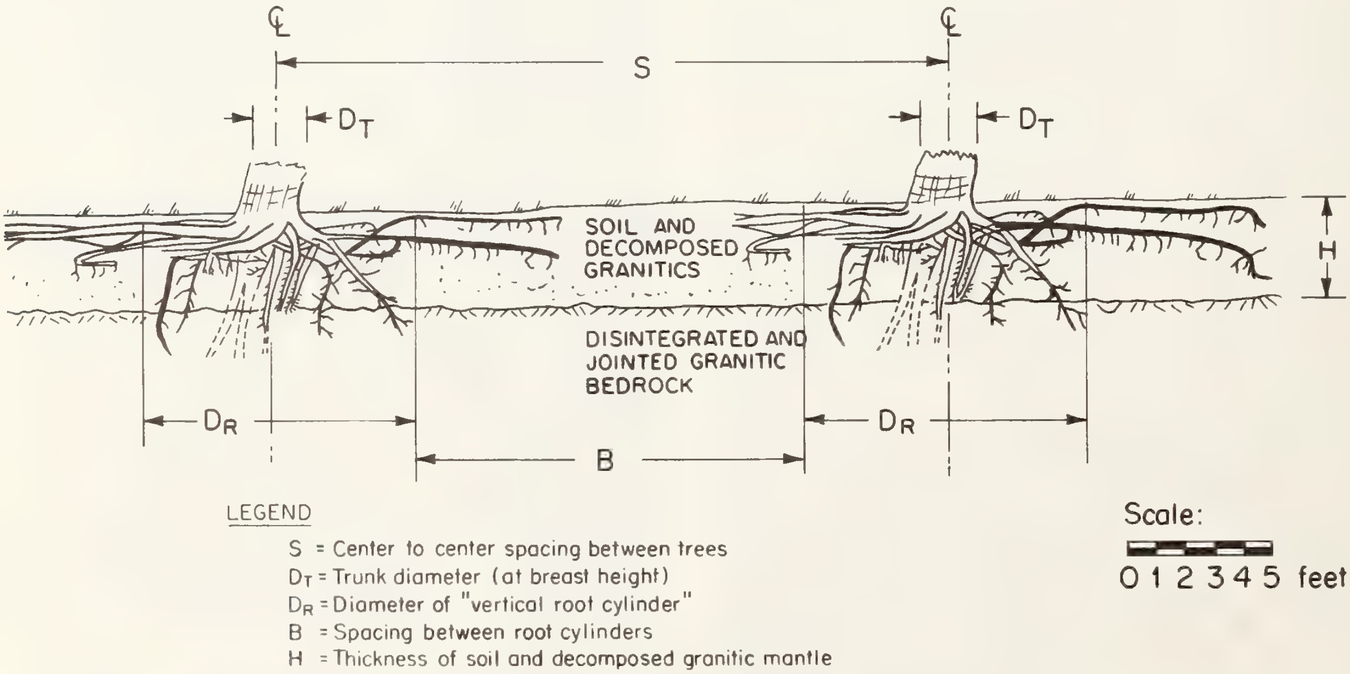

Figure 19. — Schematic diagram of spacing relationships between tree trunks and their "vertical root cylinders" in granitic slopes.

STABILITY MODELS FOR GRANITIC SLOPES

Infinite Slope Analysis — Natural Slopes

Slopes fail when the shear stress on any potential failure surface exceeds the shear strength. It is customary to express this balance of forces or stresses in terms of a ratio or factor of safety against sliding. This ratio or factor of safety is commonly defined as follows:

$$F = \frac{\text{shear resistance along critical surface}}{\text{shear forces promoting sliding on the surface}} \qquad (1)$$

Most natural granitic slopes consist of a shallow, cohesionless soil mantle overlying an inclined bedrock contact. An idealized soil profile and slope geometry were shown in figure 2. The stability of such slopes can be determined by the so-called "infinite slope analysis." This model assumes that the thickness of the sliding mass is constant and relatively thin compared to its length. This also implies that the sliding surface is parallel to the slope and approximately planar over most of its area. The infinite slope model has been used previously and with good results to analyze the stability of slopes in the Idaho batholith (Gonsior and Gardner 1971; Prellwitz 1975).

According to the infinite slope model, the factor of safety against sliding can be expressed by the following mathematical equation:

$$F = \frac{\left[\dfrac{C_s + C_R}{\tan\phi' \cos^2\beta} + (q_o + \gamma H) + (\gamma_\beta - \gamma)H_W\right] \dfrac{\tan\phi'}{\tan\beta}}{[(q_o + \gamma H) + (\gamma_{SAT} - \gamma)H_W]} \qquad (2)$$

F = factor of safety against sliding
H = thickness (depth) of soil mantle (in vertical direction)
H_W = height of piezometric surface above bedrock contact
C_s = effective cohesion of soil
C_R = shear strength increase from root reinforcement expressed as a pseudo cohesion
γ = moist density of soil (above piezometric surface)
γ_{SAT} = saturated density of soil
γ_β = buoyant density of soil ($\gamma_\beta = \gamma_{SAT} - \gamma_w$)
γ_w = density of water
q_o = vertical surcharge (from weight of vegetation)
β = slope angle or gradient
ϕ' = effective angle of internal friction of the soil

Equation 2 is a completely general expression for factor of safety, which takes into account the existence or presence of cohesion (C_s) in the soil, a slope surcharge (q_o), and a ground water table or piezometric surface in the slope (H_W). In the event these are absent, the terms in which they appear are removed from the equation. If the soil is completely dry, that is, in the absence of any piezometric surface ($H_W = O$), dry density (γ_{DRY}) may be substituted for moist density (γ) in equation 2.

The relative importance of the various parameters in equation 2, such as, cohesion as opposed to friction, and the effect on safety factor of a change in one variable, such as surcharge, is not intuitively obvious. The relative importance of each variable in the equation and direction of change that may be produced by altering input variables is best determined by conducting a sensitivity analysis using a realistic range of values for each input variable. This analysis is conducted for the study watersheds in a subsequent section of the report.

Slope vegetation and its removal affect several of the input variables in equation 2. Most noticeably or obviously affected will be the slope surcharge (q_o), piezometric height (H_W), and root cohesion term (C_R). Reduction in evapo transpiration as a result of clearcutting may also affect soil density (γ) in addition to the piezometric surface elevation. Based on the result of soil-root reinforcement studies conducted to date, the angle of internal friction of the soil (ϕ) is affected hardly at all by the presence or absence of roots (Gray 1978; Waldron 1977). The extent and consequences of forest vegetation and its removal on the stability of granitic slopes in the Idaho batholith are examined further in the next section of the report. Similar studies employing the infinite slope model have been conducted by Wu (1976), Brown and Sheu (1975), Gray (1978), and Ward (1976).

A simple theoretical model of a fiber-reinforced soil was developed by Wu (1976). This model was used by Wu to estimate the contribution of rooting strength to slope stability in analyses of both forested and cutover slopes in Southeast Alaska. A virtually identical model was developed independently by Waldron (1977) and evaluated in conjunction with direct shear tests run in the laboratory on root-permeated homogeneous and stratified soil.

A schematic illustration of the root reinforcement model proposed by Wu (1976) is shown in figure 20. The model essentially envisions an elastic root or fiber embedded in a soil matrix and initially oriented normal to the shearing surface. Deformation in the soil is resisted by tangential forces which develop along the fiber and which in turn mobilize the tensile resistance of the fiber. These tangential forces (τ on fig. 20) are produced by friction or by bonding between the fiber and surrounding soil matrix. The soil friction angle (ϕ) is assumed to be unaffected by the reinforcement. This model also assumes that tensile strength of the fibers or roots is fully mobilized during failure. This requires either fixity of the roots at their ends or roots that are long enough and/or frictional enough for the frictional or

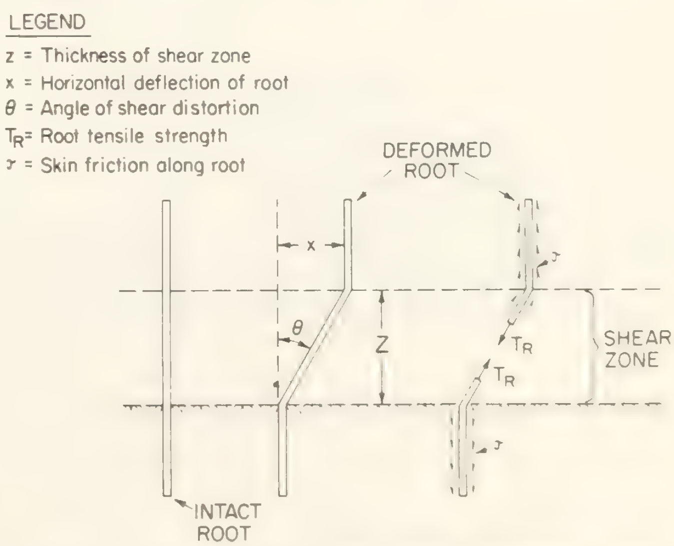

Figure 20. — Root reinforcement model. Flexible, elastic root is oriented in perpendicular direction to shear surface (after Wu 1976).

bonding strength between roots and soil matrix to exceed the tensile strength of the roots. This assumption appears justified from field examination of broken, exposed roots in shear planes of landslides (Wu 1976; Megahan and others 1978).

According to this model the tensile force that develops in the fiber can be resolved into a lateral component that directly resists shear and into a normal component that increases the normal or confining stress on the shear plane. Mathematically this translates into an increase in shear resistance or "root cohesion" C_R as follows:

$$C_R = t_R \, [\cos\Theta \tan\phi + \sin\Theta] \qquad (3)$$

where C_R = shear strength increase from root or fiber reinforcement
Θ = angle of shear distortion
ϕ = angle of internal friction
t_R = average tensile strength of roots **per unit area of soil**

The average tensile strength of fibers or roots **per unit area of soil** (t_R) can be determined by multiplying the tensile strength of the roots (T_R) by the fraction of the soil cross section filled or occupied by roots (A_R/A). Thus:

$$t_r = T_R \cdot A_R/A \qquad (4a)$$

where T_R = tensile strength of roots, psi
A_R/A = root area ratio or fraction of soil cross sectional area occupied by roots

This is an extremely useful and important relationship because it states that the root contribution to soil strength can be determined solely from measuring the tensile strength of the roots, T_R, and the fraction of the soil cross section occupied by roots, A_R/A. The root cross sectional area, A_R, can be found by counting the number of roots in different size classes, n_i, in a given soil cross sectional area, A, and then by summing the product of the root numbers in each size class times their corresponding average cross sectional area, a_i, for that size class. Thus:

$$t_R = T_R \frac{\Sigma \, n_i \, a_i}{A} \qquad (4b)$$

where n_i = number of roots in size class i
a_i = average cross sectional area of roots in size class i, square inches
A = area of soil in sample count, square inches
T_R = average tensile strength of roots, psi.

This linear relationship expressed in equation 4 between root tensile strength per unit area of soil and root area ratio has been validated by Waldron (1977) for herbaceous plant roots (barley and alfalfa) and Wu (1976) for woody plants (spruce and hemlock).

In the case of natural root systems, the tensile strength tends to vary with the size or diameter of the root (Wu 1976; Burroughs and Thomas 1977; and Gray 1978). Accordingly, the root tensile strength term must be included inside the summation and the average root tensile strength **per unit area of soil** computed by the following relationship:

$$t_R = \frac{\Sigma \, T_i \, n_i \, a_i}{A} \qquad (4c)$$

where T_i = tensile strength of roots in size class i.

Equations 3 and 4 and the model from which they are derived provide a basis for estimating the contribution of roots to soil shear strength. The only uncertain or indeterminate variable in the equations is the angle of shear distortion (Θ). This angle will vary with the amount of horizontal shear displacement and the thickness of the shear zone.

From results of laboratory direct shear tests conducted by Waldron (1977) on various root-permeated soils, the angle of shear distortion varied between 40 to 50 degrees. From the results of field observations of failures in root-permeated soil masses on slopes (Wu 1976), the angle appeared to vary between 45 and 70 degrees at most. By running a parametric variation or sensitivity analysis on equation 3, Wu (1976) showed that the bracketed term is relatively insensitive to all expected values of either friction angle (ϕ) or shear distortion angle (Θ). The bracketed term only varied from 0.92 to 1.31 for $20 \leq \phi \leq 40$ and $40 \leq \Theta \leq 70$. Thus assuming the midpoint of the range to be the most probable value for the bracketed term, the shear strength increase from root or fiber reinforcement may be estimated to an average or first approximation simply by

$$C_R \approx 1.12 \, t_R \qquad (5a)$$

or $$C_R \approx 1.12 \, T_R \cdot \frac{A_R}{A} \qquad (5b)$$

or $$C_R \approx 1.12 \frac{\Sigma \, T_i \, n_i \, a_i}{A} \qquad (5c)$$

This simple theoretical model or relationship permits an estimate of rooting contribution to shear strength based solely on a determination of the root area ratio or concentration of roots in a soil cross section and on measurements of tensile strength or resistance of the roots themselves. The validity of the model is supported by results of direct shear tests run on root-permeated soils in both field and laboratory (Endo and Tsuruta 1969; Waldron 1977).

The root reinforcement model can be used to obtain estimates of root shear-strength increase or "root cohesion" (C_R) in granitic soils of the Idaho batholith. Root density and tensile strength data from the studies by Burroughs and Thomas (1977) and Megahan and others (1978) were employed for this purpose. Calculated "root cohesions" for Rocky Mountain Douglas-fir at various elapsed times after cutting are summarized in table 4. Root cohesions were calculated using equation (5a) and root tensile strength **per unit area of soil** data for Rocky Mountain Douglas-fir reported by Burroughs and Thomas (1977). They included data for all roots in the size interval 0 to 0.4 inch (0 to 1 cm). As noted previously inclusion of roots up to 0.4 inch (1 cm) in diameter corresponds to a root area ratio of 0.045 percent. This ratio is a reasonable **lower bound** estimate for root concentration across a potential failure surface in the shallow, coarse-textured granitic soils of the Idaho batholith. With increasing time after felling, both the number of roots and the tensile strength of the remaining roots decrease; this accounts for the decrease in root cohesion (table 4).

The tabulated data indicate that shear strength increases from root reinforcement up to 1.5 lb/in² (10.3 kPa) are possible in granitic soils for initial root area ratios as low as 0.045. Furthermore, the data show that some 60 to 70 percent of this strength is lost due to root deterioration or decay 5 to 10 years after cutting. This elapsed time coincides with the period of greatest landslide activity as observed by Megahan and others (1978), figure 7. With slightly higher root area ratios (up to 0.15 percent), which appear to be entirely possible based on data from Megahan and others (1978) and Wu (1976), the rooting contribution to soil shear strength increase will be still higher (assuming tensile strength of the roots remains the same).

Table 4. — "Root cohesion" of soil at various elapsed times after felling Douglas-fir for root size class 0 to 1 centimeter

Residual root cohesion[1] (C_R), lb/inch^2			
t = 0 (fresh)	t = 1 year	t = 5 years	t = 10 years
1.50	0.70	0.50	0.40

[1]Calculated from equation (5a) and root tensile strength data in Burroughs and Thomas (1977).

SOIL ARCHING RESTRAINT MODEL

Arching in slopes occurs when soil begins to move through and around a row of piles (or trees) firmly embedded or anchored in an unyielding layer. Under the right conditions, the trees are in effect both cantilever piles and abutments of "soil arches" that form in the ground upslope from the trees. The requirement of firm anchoring or embedment of trees in an unyielding layer of a slope can occur under the following conditions:

(1) Overlying an inclined bedrock contact in shallow residual soils or glacial till.

(2) In sandy slopes, where tree stem bases are deeply buried as a result of sand accretion.

Other conditions pertaining to spacing and diameter of the tree trunks, thickness and inclination of the yielding portion of the soil profile, and shear strength properties of the soil also determine arching effectiveness.

An arching theory developed for soil slopes by Wang and Yen (1974) is based on a semi-infinite slope model and rigid-plastic-solid soil behavior. Their theory was developed for a single row of embedded piles (of diameter d) spaced a distance (B) apart across a slope as shown schematically in figure 21. According to this theory, the average arching pressure (p) in a slope and the critical spacing (B_{CRIT}) for arching to occur are given by the following equations:

$$\frac{p}{\gamma H} = \left[\frac{m\cos\beta\sin\beta - K_o\cos\beta\tan\phi - \frac{2C_s}{\gamma H}\cos\beta - m\cos^2\beta\tan\phi_1 - \frac{c_1}{\gamma H}m}{2K_o\cos\beta\tan\phi}\right]$$

$$\times\left[\{1-\exp(-2K_o n\cos\beta\tan\phi)\} + 1/2K_o\exp(-2K_o n\cos\beta\tan\phi)\right] \qquad (6)$$

$$\text{and } B_{CRIT} = \frac{H K_o (K_o + 1)\tan\phi + \frac{2C_s}{\gamma}}{\cos\beta(\tan\beta - \tan\phi) - \frac{c_1}{\gamma H\cos\beta}} \qquad (7)$$

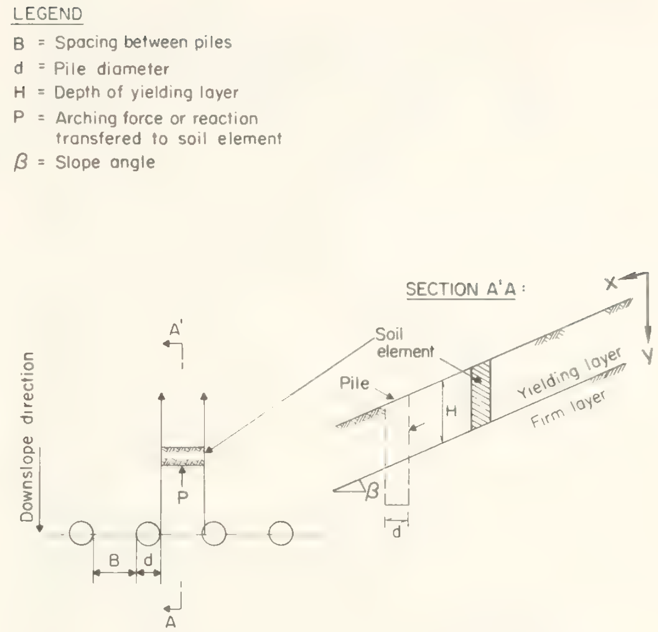

Figure 21. — State of plastic deformation and soil arching action around a row of piles (trees) embedded in a slope (from Wang and Yen 1974).

where B = clear spacing or opening between piles
B_{CRIT} = critical clear spacing between piles
C_s = cohesion in soil
c_1 = cohesion along basal sliding surface
H = depth of yielding or sliding plane
K_o = coefficient of lateral earth pressure at rest
m = B/H = relative width or dimensionless spacing
n = X/B = relative distance (in direction of slope)
p = average lateral pressure or arching pressure
β = slope angle
γ = unit weight of soil
ϕ and ϕ_1 = angle of internal friction in soil and along basal sliding surface, respectively.

The total force (P) developed against a pile of diameter (d) embedded in a slope with a thickness or depth of yielding soil (H) is given by:

$$P = \frac{K_o}{2}\gamma H^2 d + \left(\frac{K_o}{2}\gamma H - p\right)BH \qquad (8)$$

The load on each pile embedded in a slope is thus the summation of two loads, one from the pressure at rest of the soil immediately uphill from the pile, similar to the lateral pressure on a retaining wall. The other is the soil arching pressure transferred to the adjacent piles as if each pile is an abutment of an arch dam. When the average lateral pressure (p) approaches zero, arching action is a maximum.

RESULTS OF ANALYTICAL AND FIELD STUDIES

Piezometric Responses of Slopes to Vegetation Removal

A number of hydrologic processes are regulated by vegetation on a forested slope. For the present study area, important processes are snow accumulation and melt and factors affecting total evaporation losses including interception, transpiration, and direct evaporation from the soil. These processes in turn influence slope stability by helping to regulate the water content of the unsaturated soil moisture zone and the depth of any underlying piezometric surface. The net effect of vegetation removal is to reduce evapotranspiration losses and to increase snow accumulation and snowmelt rates thereby creating a tendency to raise the piezometric surface.

Increased soil moisture contents at the end of the growing season document the fact that evapotranspiration losses were reduced following clearcutting and fire on the study watersheds. Also snow survey and snowmelt lysimeter data verify increased springtime snow accumulation and snowmelt rates following timber removal (Megahan, unpublished data). The combined effect of an increased snowpack melting faster in conjunction with a greater carryover of fall soil moisture storage causes an increase in peak springtime piezometric depths compared to the forested condition (fig. 22). The piezometric data shown are the annual peak values for the piezometer on each watershed that registered the greatest water depth throughout the entire study period. The snowpack data are from the nearby Silver Creek study area that remained undisturbed throughout the course of the present study.

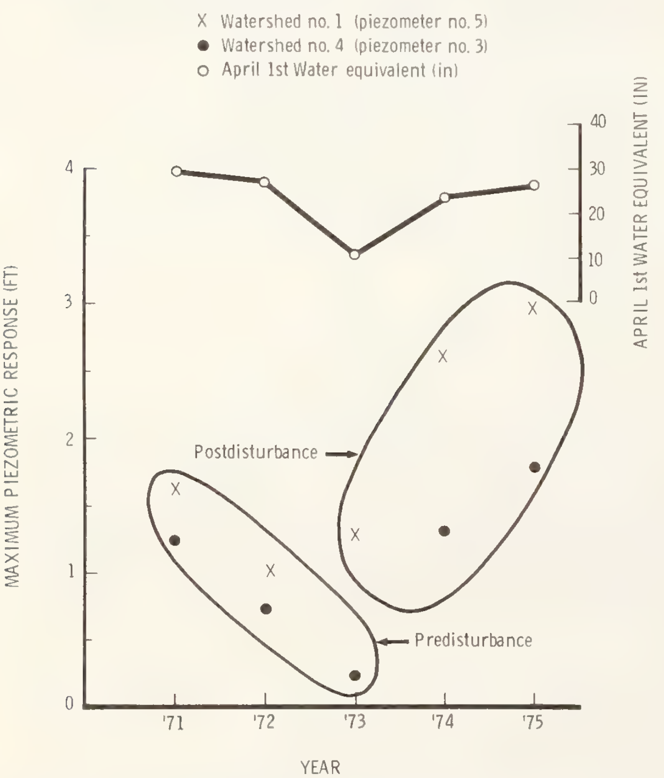

Figure 22. — Annual peak piezometric response for peak sample points on Watersheds No. 1 and No. 4 and corresponding snow accumulations.

The consistently greater piezometric responses on Watershed No. 1 as compared on Watershed No. 4 reflect the greater potential drainage area for piezometers on No. 1 relative to No. 4. Water depths on both drainages decreased from 1971 to 1972 in response to a smaller snowpack in 1972. The 1973 snowpack was unusually low (there was a 7 percent chance of having a snow water content equal to or less than the recorded value) and the piezometric levels on the undisturbed Watershed No. 4 dropped accordingly.

A similar trend in piezometer levels did not occur, however, on Watershed No. 1, which had been clearcut logged the previous November. Rather, the maximum piezometer level actually exceeded those recorded in 1972 when snow water contents were much greater (there was an 81 percent chance of having a snow water content equal to or less than the recorded value in 1972). The late fall cutting date for Watershed No. 1 prevented the development of differences in growing season soil moisture storages on the two study watersheds; therefore, the increased piezometric levels on Watershed No. 1 are mainly the result of differences in snow accumulation and melt during the previous winter and spring.

The following summer, the total soil moisture storage on Watershed No. 4 decreased more rapidly than on Watershed No. 1 because of reduced evapotranspiration losses caused by the timber removal on Watershed No. 1. By mid-August of 1973, 49 percent more water was stored in the 12- to 60-inch (30- to 152-cm) depth on Watershed No. 1 (a total of 5.8 inches [14.8 cm] on Watershed No. 1 and 3.9 inches [9.9 cm] on Watershed No. 4). On August 20, 1973, both watersheds were burned in a wildfire that killed all nonsprouting vegetation. In the spring of 1974, piezometric levels were greatly increased on Watershed No. 1 relative to predisturbance levels even though the April 1 snow accumulation was less than the two prelogging years studied. The difference reflects both changes in evapotranspiration losses and in snow accumulation and melt rates. Piezometric levels also increased on Watershed No. 4, but probably not to the maximum because of the development of a partial soil moisture deficit prior to the fire. April 1 snow depths increased slightly in 1975, relative to 1974, but still were below pretreatment amounts. Large increases in piezometric levels occurred on both study watersheds in response to combined effects of decreased evapotranspiration and snow accumulation and melt.

These data do not lend themselves to rigorous statistical analysis because of limited sample sizes. A simple graphical analysis relating the annual peak piezometer depth to the corresponding April 1 snow water content is informative, however, because it suggests the relative effects of vegetation removal on piezometric levels (fig. 23). A simple linear regression was fitted to the three predisturbance data points for Watershed No. 4. In spite of the limited data points, the regression had an r square value of 0.85 and a standard error of 0.27 feet (0.09 m). The regression coefficient was significantly different from zero at the 85 percent confidence level. By using the snow water contents for 1974 and 1975 to predict the piezometric levels for these years and by comparing predicted to measured piezometric values, we can estimate increases of about 65 percent and 100 percent in soil water levels for 1974 and 1975, respectively. A similar analysis is not possible for Watershed No. 1 because there are only two pretreatment data points. If the assumption is made, however, that the regression slope is the same as for Watershed No. 4 and that the regression line

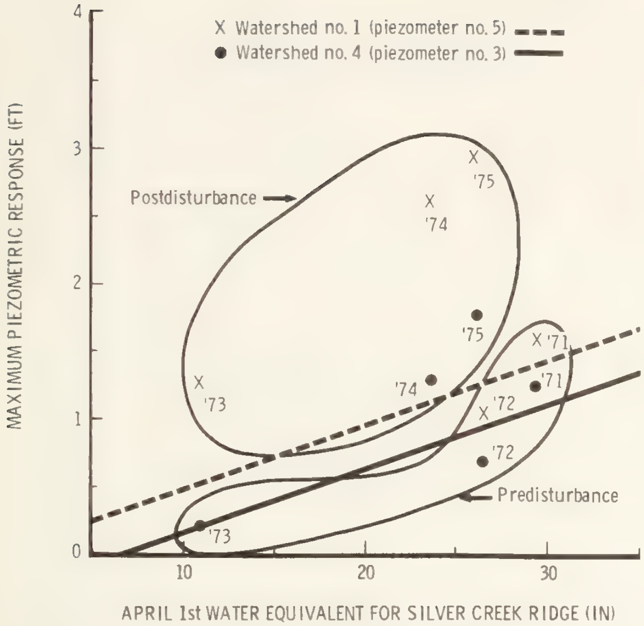

Figure 23. — Annual peak piezometric response for peak sample points on Watersheds No. 1 and No. 4 versus annual April 1 snow water content in inches.

passes through the average for the two pretreatment years (dashed line, fig. 23), we obtain estimates of changes in soil moisture levels of 140, 134, and 140 percent for 1973, 1974, and 1975, respectively, for Watershed No. 1.

Estimated increases in maximum piezometric levels range from 65 to 140 percent following clearcut timber harvest and/or wildfire. We want to emphasize the fact that these increases are not statistically significant. The increases, however, are relatively consistent for both watersheds for all postdisturbance years over a wide range of climatic conditions. Moreover, the documented onsite hydrologic responses of increased soil moisture carryover and increased snow accumulation and melt rates following vegetation removal would tend to cause increased piezometric levels. Everything considered, we feel that peak piezometric levels were increased about 100 percent as the result of clearcutting and relatively intense wildfire on the study area.

Stability Relationships

SOIL SHEAR STRENGTH

The results of borehole shear tests and field density measurements in Watershed No. 1 are summarized in table 5. Soil friction angles (ϕ) not only tended to vary with location, but with depth as well. Friction angles varied from 29 to 39 degrees, and generally increased with depth to a limiting value of 38 to 39 degrees at the contact between soil (decomposed granitics) and fractured, disintegrated bedrock. The friction values reported in table 5 are station averages for the surface soil alone. No cohesion was detected in any of the borehole tests. The gradation of a composite sample taken from the 24- to 36-inch (61- to 91-cm) depth of the soil horizon in Watershed No. 1 is shown in figure 24. The soil consists of 10 percent fine gravel, 86 percent sand, and 4 percent by weight silt size material; it would be classified as a well-graded sand (SW), according to the Unified Classification system. In-situ densities ranged from 92 to 101 lb/ft^3 (1.47 to 1.62 g/cm^3) with an average value of 96 lb/ft^3 (1.54 g/cm^3). Densities tended to increase with depth as did the friction angle of the soil. Only the mean density (96 lb/ft^3) is tabulated in table 5. Subsequent sensitivity analyses showed that such small variations in soil density from station to station had a negligible influence on calculated slope stability; hence the reason for tabulating only the mean.

Table 5.—Summary of soil-slope data for granitic soil in the Pine Creek study watershed

	Station number					
Slope or soil parameters	**1**	**2**	**3**	**4**	**5**	**6**
Friction angle,[1] degrees	34	29	29	34	32	37
Slope angle, degrees	30	28	29	32	31	40
Soil depth, inches	30	36	30	30	30	48
Soil density,[2] lb/ft^3	96	96	96	96	96	96
Dry density,[2] lb/ft^3	88	88	88	88	88	88
Saturated density,[2] lb/ft^3	117	117	117	117	117	117
Cohesion, lb/inch^2	0	0	0	0	0	0

[1]In-situ borehole shear test. No cohesion intercept detected.

[2]Mean value based on several measurements of field density and water content at different stations.

The soil shear strength parameters, densities, void ratios, and gradations measured in the Pine Creek study watersheds are comparable to those reported by Gonsior and Gardner (1971) during extensive field and laboratory tests of granitic soils in the Zena Creek timber sale area in the Payette National Forest. Most of the soils investigated by them had slightly higher silt size fractions and so were classified as well-graded silty sands, or SW-SM materials, according to the Unified Classification.

Gonsior and Gardner (1971) conducted numerous direct shear and triaxial compression tests to investigate the effect of unit weight and moisture content upon the shear strength of granitic soils. Their test results showed that strengths based upon effective stress parameters exhibited negligible variation over a wide range of conditions. For design purposes, they recommended 35 and 0 as reasonable values for the angle of internal friction (ϕ) and soil cohesion (C_s), respectively. Shear strength envelopes measured in triaxial compression indicated slight residual cohesive strength (on the order of 2 lb/in^2 [14 kPa]) in most tests on saturated specimens. Gonsior and Gardner (1971) advise, however, that some of the cohesion measured in triaxial tests on saturated specimens could be accounted for by partial saturation, a curved failure envelope, or by membrane resistance; no corrections were made for this factor.

These findings are also corroborated by Lumb (1962) who examined the influence of variation in cohesion and friction angle with void ratio and degree of saturation. His tests were run on both undisturbed and remolded samples of decomposed granite with fine, medium, and coarse gradation. Considerable "apparent cohesion" was manifest in partially saturated specimens as a result of capillary forces. As expected, apparent cohesion tended towards zero at full saturation (that is, below a piezometric surface) in all soils tested, fine or coarse grained.

Undoubtedly, some residual soil cohesion does exist in granitic soils; borehole shear test results notwithstanding. In the first

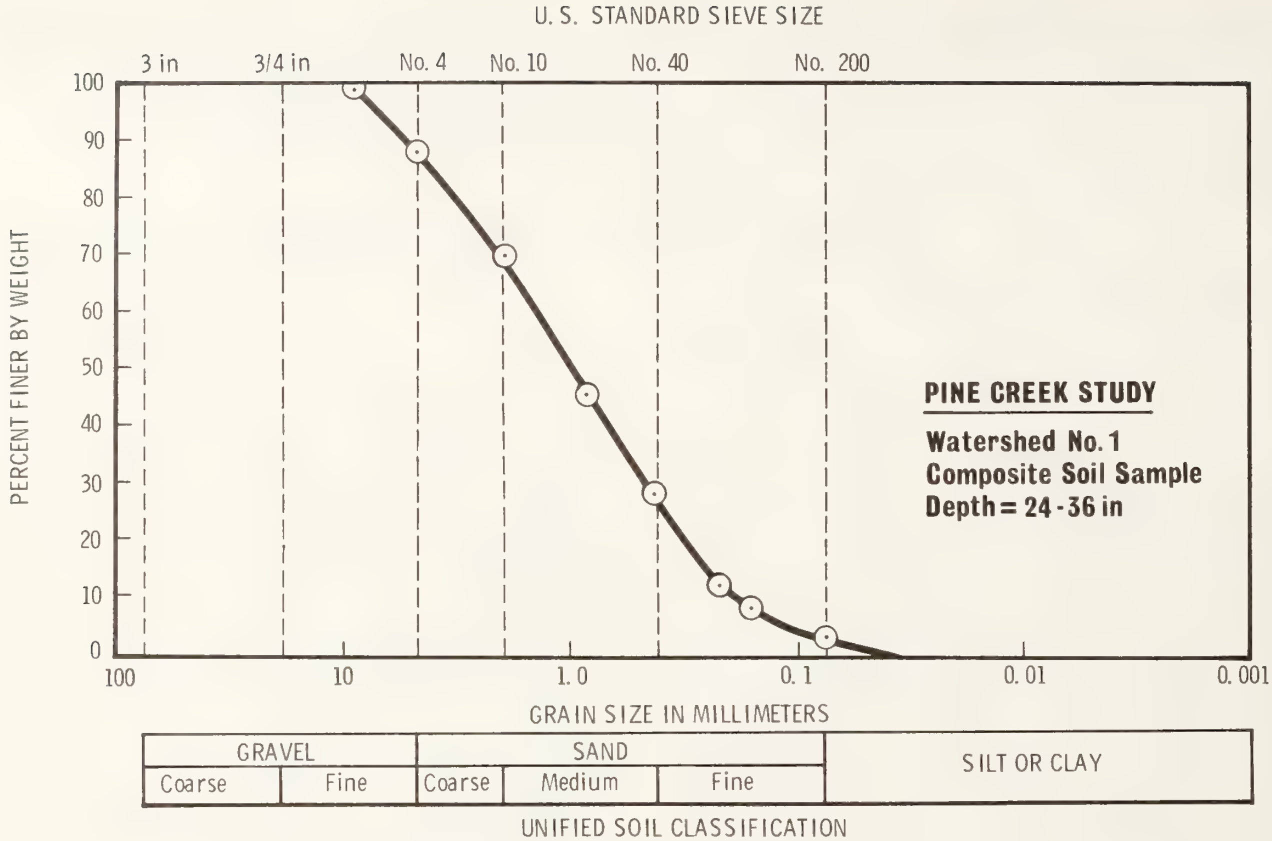

Figure 24. — Grain-size distribution of composite soil sample from Watershed No. 1.

place, the borehole shear test often yields low or nonexistent values of cohesion (Wineland 1975). Secondly, full or complete saturation is required to eliminate apparent cohesion as a result of capillary action. Lastly, some cohesion must be present to explain the stability of what otherwise would often be a failed slope, particularly in the case of cut slopes.

Analysis of actual failures in both natural and cut slopes in the Idaho batholith by Gonsior and Gardner (1971) suggests that cohesion up to 0.9 lb/in^2 (6.2 kPa) may be mobilized. A similar value was reported by Prellwitz (1975) in his analysis of granitic slopes in the batholith. Prellwitz (1975) suggests that a cohesion of 0.76 lb/in^2 (5.2 kPa) is reasonable for soils above the phreatic surface and 0.35 lb/in^2 (2.4 kPa) below for SW-SM materials.

Much higher cohesions have been reported in laboratory triaxial tests on some granitic soils of the batholith (Hampton and others 1974).[1] Sample sites in this study were purposely selected to provide a wide range in the weathering properties of granitic rocks with the sampling heavier in the more weathered rocks. Higher cohesion would be expected under these conditions because more advanced chemical weathering of the bedrock has occurred, causing formation and accumulation of clay colloids. Hydrolysis of mica and feldspars leads to formation of clay minerals such as illite and kaolinite. The absence of strong solution and eluviation leads to their accumulation. These factors may combine to produce a finer grained, more cohesive, and correspondingly less frictional soil as shown by the results of triaxial compression tests in figure 25.

Highly weathered bedrock conditions are relatively rare in the Idaho batholith because they are generally associated with shear zones and zones of secondary hydrothermal alteration. Accordingly, high cohesion values such as those shown in figure 25 probably occur on less than 5 percent of the upland slopes of the batholith. Such soil conditions were not present in the Pine Creek study watersheds as evidenced by the shear strength test results reported in table 5.

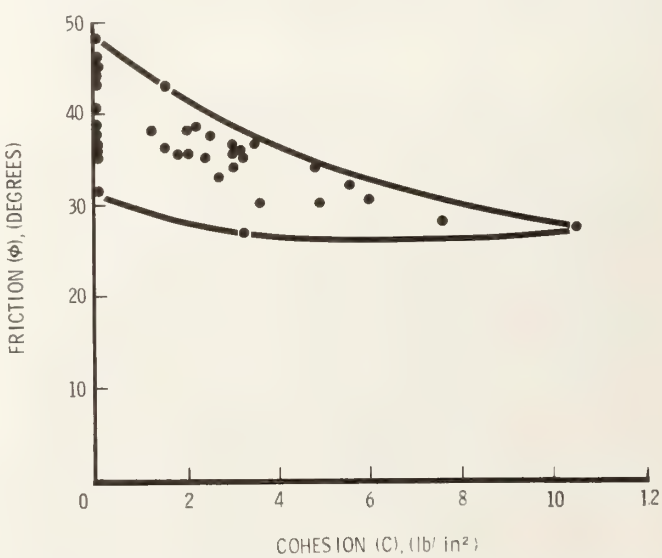

Figure 25. — Relationships between angle of internal friction and cohesion for various batholith soils (from Hampton and others 1974, footnote 1).

SOIL ARCHING RESTRAINT

Preliminary analyses of field data obtained from forested, sandy slopes on the Idaho batholith indicate that these slopes meet theoretical criteria for arching restraint between trees. Tree spacings, or more importantly the width of openings between "vertical root cylinders" are of the right order of magnitude for soil arching to manifest itself according to the Wang-Yen theory (Wang and Yen 1974). Tree trunks and their associated "vertical root cylinders," which are firmly anchored to bedrock (fig. 19), potentially can behave as arch abutments.

Openings between vertical root cylinders appear to average around 30 feet (9.1 m) based on stem counts in forested plots on the nearby Silver Creek study area (table 3). These data were obtained from large survey units which include some unforested areas in streams, brush, and rock outcrop. On a smaller more localized scale, spacings are considerably less, particularly in groves of trees (fig. 26). Based on these last field observations, the width of opening between vertical root cylinders in the slopes averages about 6 to 7 ft. (1.8 to 2.1 m).

The maximum allowable opening or critical distance (B_{CR}) between piles (or trees) embedded in a slope can be calculated from soil arching theory. This critical distance is shown plotted in figure 27 using the soil arching theory for slopes derived by Wang and Yen (1974). The critical distance is plotted versus cohesion for various assumed values of residual friction and cohesion (ϕ_1, c_1) along the basal sliding surface. Other soil and slope parameters used in the analysis are typical of shallow coarse-textured, granitic soils overlying a steep bedrock rock contact (β = 40°, ϕ = 35°, H = 3 ft [0.9 m] γ = 100 lb/ft^3 [1.6 g/cm^3]).

The soil arching analyses show that the critical distance in a shallow mantle is very sensitive to cohesion, particularly cohesion along the basal sliding surface (c_1). If no cohesion is assumed, and the residual friction (ϕ_1) along the basal sliding surface is one-half the peak friction (ϕ), then the critical spacing is 4 ft (1.2 m). On the other hand, if a cohesion (C_s) of only 0.35 lb/in^2 (2.4 kPa) is assumed with the residual cohesion (c_1) along

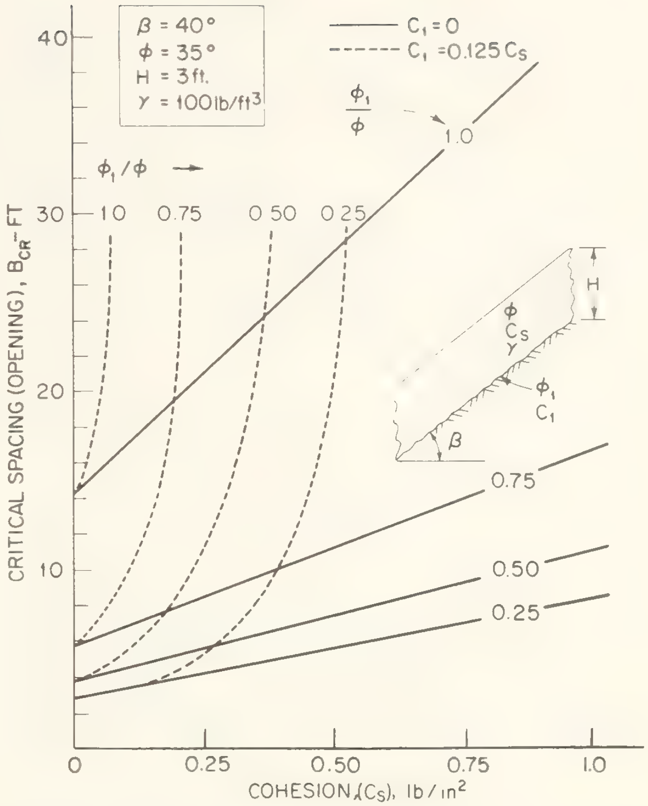

Figure 27. — Theoretical critical openings (B_{CR}) versus cohesion for piles (trees) embedded in a steep, sandy slope (β = 40°, ϕ = 35°, H = 3 ft.). Influence of cohesion and friction along the base (ϕ_1, c_1) is also shown.

the basal sliding surface a mere 12 percent of this value, then the critical spacing increases to 21 ft (6.3 m). This distance usually approaches or exceeds the size openings between "vertical root cylinders" observed in the field, particularly in groves of trees (fig. 26). Based on his analysis of granitic slopes in the batholith, Prellwitz (1975) suggested that 0.35 lb/in^2 (2.4 kPa) is a reasonable lower limit for cohesion of soils beneath the phreatic surface. With slightly higher values of cohesion, the critical distance increases further thus insuring that soil arching effects will be manifest. These values of cohesion in granitic soils are well within reason. Possible sources of cohesion or apparent cohesion include root reinforcement, cementation, clay binder, and capillary stresses (above the phreatic surface).

Figure 26. — Row of ponderosa pine trees at spacings sufficiently close to manifest soil arching restraint between trees. Silver Creek study area, Boise National Forest.

SENSITIVITY ANALYSES

The relative importance of various soil-slope-hydrologic parameters on slope stability and the direction of change in slope safety factor that may be produced by altering these parameters may be determined by conducting sensitivity analyses or parametric variation studies. These same studies also permit evaluation of effect of vegetation removal on slope stability through the influence of removal on the parameters themselves.

There are several types of slope sensitivity analyses that can be conducted. All are based in the present case on the infinite slope model and on the effect of altering input variables on the general stability relationship expressed in equation 2.

Table 6 includes a summary of stability relationships for each of the stations or locations where borehole shear tests were conducted. Shown in table 6 are calculated factors of safety for each station based on existing or measured values of soil depth

Table 6. — Summary of stability calculations at different stations for granitic soil in the Pine Creek study watershed, Idaho

Stability calculations	Station number 1	2	3	4	5	6
Factor of safety[1] (F)	1.2	1.04	1.0	1.1	1.04	0.9
Critical piezometric level[2] (H_{cr}), inch	6.5	2.1	0	3.2	1.7	N/A
Required cohesion for stability, lb/inch²						
H_w/H = 0 (dry)	0	0	0	0	0	0.12
= 0.5	0.14	0.24	0.23	0.20	0.20	0.53
= 1.0 (saturated)	0.40	0.52	0.46	0.45	0.46	0.93

[1]Based on infinite slope model (equation 2.)

[2]Piezometric height (above failure surface) at which F = 1.0 for slope and soil parameters given in table 5.

(H), local slope angle (β), soil density (γ or γ_D), friction angle (φ), and soil cohesion (C_s). The calculated factors of safety are close to unity and suggest the slope is only marginally secure. The calculations are based on zero cohesion (C_s = 0) and dry slopes (H_W = 0). Critical piezometric levels (still assuming zero cohesion) are also shown. The slope should theoretically fail at the critical piezometric level (F = 1.0). These critical piezometric levels are on the order of a few inches. The fact that the entire slope did not fail when pieometric levels in excess of these critical values developed in the slope (figs. 22 and 23) means that some cohesion must be present. Required cohesion to prevent failure at various piezometric levels is also calculated and tabulated. Values range from 0.4 to 0.9 lb/in² (2.8 to 6.2 kPa) at full saturation (H_W = H). These residual cohesions are consistent with values reported by Gonsior and Gardner (1971) and Prellwitz (1975). These observations are based, of course, on the assumption that the infinite slope model adequately represents stability conditions in granitic slopes of the Idaho batholith. Limitations of the infinite slope theory in this regard are discussed by Hartsog and Martin (1974), but do not appear to apply in this case.

The influence of both friction and cohesion on the factor of safety of a typical granitic slope with a shallow soil mantle is shown in figures 28 and 29. A slope thickness of 36 inches (92 cm), slope gradient of 35°, and soil densities of 88 and 117 lb/ft³ (1.4 and 1.9 g/cm³), dry and saturated, respectively, were selected for the analysis. Factor of safety is plotted against cohesion for various values of friction and piezometric elevation in the slope. As shown in the figures, stability is far more sensitive to soil cohesion than to friction angle, particularly when slope becomes fully saturated (H_W = H). It is also clear from this analysis that some cohesion must exist in steep slopes in order to provide the critical margin for stability when piezometric levels rise in the slope. Little cohesion is required to maintain a stable slope. Only 0.66 lb/in² (4.6 kPa) is needed at a friction angle of 19° and a slope angle of 35° (tanφ/tanβ = 0.50) when H_W/H = 0.5 (fig. 28). For these same conditions of slope and friction angle, at full saturation, (H_W/H = 1.0), the required cohesion is 0.88 lb/in² (6.1 kPa) (fig. 29).

The influence of a rise in piezometric surface on the factor of safety (all other factors held constant) can also be determined.

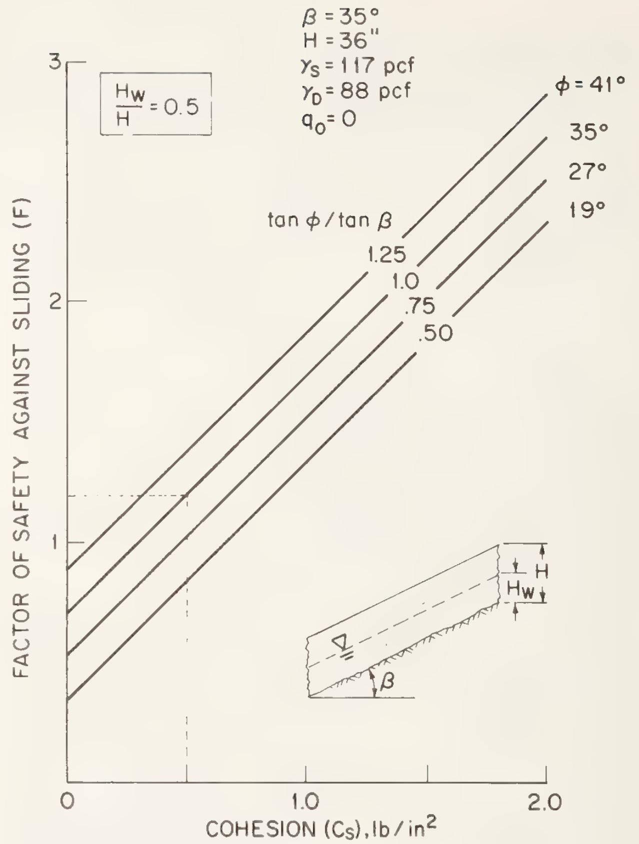

Figure 28. — Influence of cohesion on the stability of a sandy residual soil resting on an inclined bedrock contact. $\frac{H_W}{H}$ = 0.5.

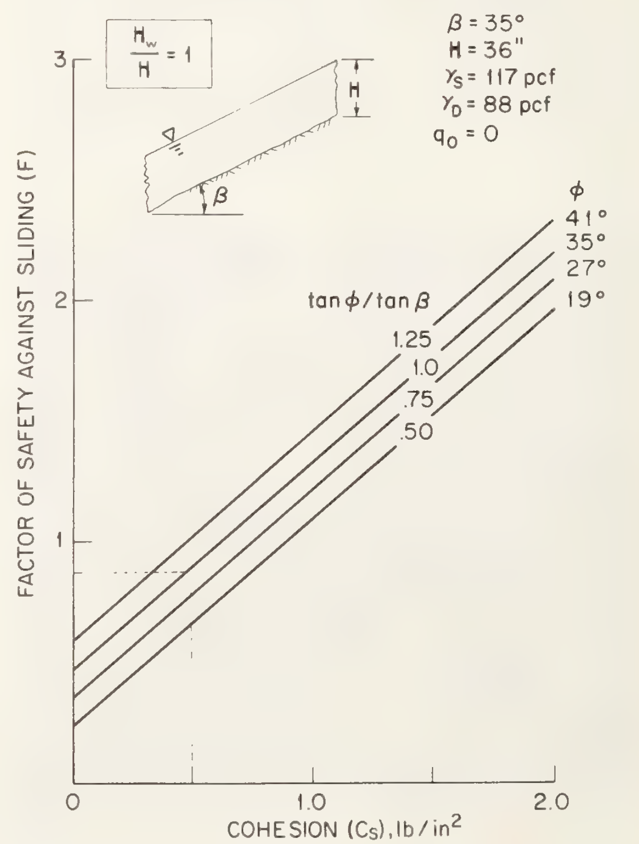

Figure 29. — Influence of cohesion on the stability of a sandy residual soil resting on an inclined bedrock contact. $\frac{H_W}{H}$ = 1.

In this example, a cohesion of 0.5 lb/in² (3.4 kPa) and a friction angle of 35° are assumed. When the piezometric surface doubles in height, the factor of safety drops below one. This relationship is shown by the dashed lines in figures 28 and 29, respectively.

Yet another type of sensitivity analysis (Simons and others 1978)[2] can be employed that not only reveals the sensitivity, but also the direction of change in slope safety factor corresponding to a change in any input variable in the infinite slope equation. This approach is useful for examining the influence of vegetation removal on slope stability and the influence of changes in such variables as surcharge, the effects of which are more obscure or counter-intuitive.

This approach is conducted in four steps. First, a realistic range of values (ΔX_i) is selected for each input variable (X_i). Second, a base safety factor is computed by using the median values for all variables. Third, each input parameter is changed across its range of values and a new factor of safety is computed for each altered input. Fourth, the results are plotted as a relative percentage.

This sensitivity analysis was conducted for the range of input variables and their median values shown in table 7. These medians are believed typical of conditions for natural slopes in forested watersheds in the Idaho batholith. The ranges include conditions believed typical of conditions in both forested and cutover watersheds. In order to conduct the sensitivity analysis, the factor of safety equation was rewritten in a slightly different form as follows:

$$F = \frac{\dfrac{2(C_s + C_R)}{\gamma_w H \sin 2\beta} + \left[\dfrac{q_o}{\gamma_w H} + \left(\dfrac{\gamma_{SAT}}{\gamma_w} - 1\right) M + \dfrac{\gamma}{\gamma_w}(1-M)\right]\dfrac{\tan \phi'}{\tan \beta}}{\left[\dfrac{q_o}{\gamma_w H} + \left(\dfrac{\gamma_{SAT}}{\gamma_w}\right)M + \dfrac{\gamma}{\gamma_w}(1-M)\right]} \qquad (9)$$

where M = relative ground water height $(= \frac{H_w}{H})$

Table 7. — Range of input variables and their estimated medians for soil and slope conditions in watersheds of the Idaho batholith

Input variable	Range	Median
Variables not particularly influenced by vegetation:		
β	20-40°	30°
ϕ'	27-42°	35°
H	12-48 in	30 in
γ	90-120 lb/ft³	100 lb/ft³
γ_{SAT}	110-140 lb/ft³	120 lb/ft³
C_s	0-2 lb/in²	0.75 lb/in²
Variables strongly influenced by vegetation:		
q_o	0-200 lb/ft²	20 lb/ft²
C_R	0-1.5 lb/in²	0.5 lb/in²
M	0-1	0.25

[2]Simons, D. B., R. M. Li, and T. J. Ward. 1978. Mapping of potential landslide areas in terms of slope stability. Report prepared by Eng. Res. Cent., Colo. State Univ. for USDA For. Serv., Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 74 p.

The results of the sensitivity analysis shown in figure 30 revealed that some inputs have a linear effect on F while others, notably H and β, have strongly nonlinear effects. Factor of safety is quite sensitive to both root (C_R) and soil cohesion (C_S). In contrast, the slope safety factor is relatively insensitive to changes in density (γ) and surcharge (loss) q_o. Changes in soil friction (ϕ) do not have nearly as much influence on safety factor as changes in cohesion (C_S and C_R). This finding corrobrates the results shown in figures 28 and 29. The influence of relative ground water height (M) or piezometric elevation is intermediate in effect, except at very high ground water elevations ($M \rightarrow 1$) where safety factors decrease sharply.

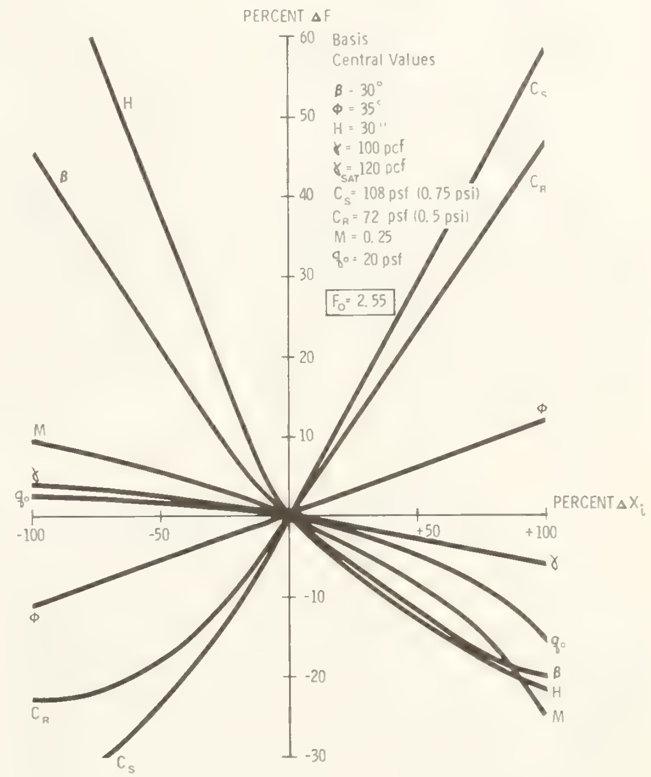

Figure 30. — Percent change in slope safety factor versus percent change in input variables. Base safety factor (F) was computed using the median or central value for all variables (table 7).

CONSEQUENCES OF VEGETATION REMOVAL

The preceding sensitivity analyses can be used to help evaluate the consequences of vegetation removal on the stability of slopes in the Idaho batholith. The input variables most strongly influenced by vegetation are M, q_o, and C_R. Removal of slope vegetation tends to decreased root cohesion (C_R), increased piezometric levels (M), and decreased slope surcharge (q_o). The net effect of these changes is to adversely affect stability; their extent and significance will be explored further. An exception appears to be surcharge that decreases following clearcutting, which should improve stability based on the sensitivity analysis previously discussed. On the other hand, this improvement is marginal; moreover, it can be shown that at low values of cohesion and high ground water elevations surcharge has a beneficial influence (Ward 1976).

Impact of Foliage Loss

Removal of slope vegetation results in a temporary but significant loss of foliage available for interception and transpiration of water. This in turn leads to wetter conditions and higher piezometric levels in a slope. Results of the Pine Creek study support this conclusion (figs. 22 and 23) as do results of other hydrologic investigations on effects of timber removal (Gray and Brenner 1970; Bethlahmy 1962; Brenner 1973). The impact of vegetation removal on soil moisture changes in a slope appears to be most critical the first year after cutting. Studies by Hallin (1967) showed that, after 3 years, low vegetation that invades a cutover site is nearly as effective as old-growth timber in depleting moisture.

The results of soil water piezometry studies in Watersheds Nos. 1 and 4 indicate that removal of vegetation by clearcut logging can increase piezometric levels as much as 100 percent. Critical piezometric levels shown in table 6, that is, the minimum head required to cause slope failure assuming no soil cohesion, were frequently exceeded. The occurrence of slides in the slope above the road cut in both watersheds (figs. 10-13) and in other watersheds in the vicinity (table 2) reflects the low margin of safety under high piezometric conditions. On the other hand, the absence of massive and pervasive slope failures suggests that some residual cohesion must be present. Required cohesions for local stability in Watershed No. 4 for different piezometric heads are also shown in table 6. These cohesions could be provided in whole or in part by root reinforcement.

Impact of Root Decay

The importance of cohesion on stability was clearly established in the preceding sensitivity analyses. The root reinforcement model coupled with root tensile strength and root distribution data show that live roots can provide a large fraction of the total or apparent cohesion present in granitic soils in the batholith. Conversely, studies of root strength loss with time after cutting (Burroughs and Thomas 1977) and landslide frequency with time after cutting (Megahan and others 1978) indicate progressive loss of root cohesion following clearcutting. Megahan's data suggest that landslides are most frequent 4 to 10 years after logging. These data are consistent with findings of other investigators (for example, Bishop and Stevens 1964; Swanston and Walkotten 1970). The time of minimum stability represents a crossover point between the growth and decay curves of root systems of slope vegetation. Root strength decline after tree felling is undoubtedly both species and site dependent (Burroughs and Thomas 1977). The timing or occurrence of slope failures is thus dependent on the amount of residual stand on the slope and the rate of establishment of new vegetation relative to the root strength decline of previously cut trees (Kitamura and Namba 1966).

Loss of Buttressing and Soil Arching Action

Analysis of spacing relationships and rooting morphology of trees in forested slopes of the Idaho batholith indicate the soil arching between trees may play an important role in restraining soil movement. Several examples of buttressing action by embedded tree trunks and root systems were observed (figs. 4 and 5). Gonsior and Gardner (1971) reported similar examples in their analyses of slope failures in the Idaho batholith. They recommended, in fact, that barriers of live trees should remain undisturbed immediately below the toe of fill slopes and above the cut slope.

Removal of all large diameter stems by clearcutting, of course, gradually eliminates any soil arching restraint or soil arching action. The stumps will temporarily provide restraint, but when the roots rot and decay these anchor points or "arch abutments" will actually become zones of weakness in the slope. This will occur because as roots rot and disappear voids with no shear strength will be left behind, or infilling with weak colloids may occur in the old root channels. In addition, former root channels may provide entry points for water and thus facilitate rapid buildup of pore pressures.

Loss of Surcharge

The sensitivity analysis reported showed that decreasing the vertical surcharge (q_o) by removing slope vegetation has a beneficial influence on stability, but only a slight one. Under certain conditions, surcharge can actually enhance stability. Ward (1976) showed that this occurs under the following circumstances:

$$(C_s + C_R) < \gamma_w H_W \tan \phi \cos^2\beta \qquad (10)$$

This relationship shows that surcharge is beneficial for low cohesion values, high piezometric levels, and relatively gentle slopes. Assuming the worst case of maximum rise in piezometric surface ($H_W = H$) and substituting the median values in table 6 for the variables on the right-hand side of equation (10), a limiting total cohesion of 0.57 lb/in^2 (3.9 kPa) results. This cohesion is quite possible as an upper, limiting value in many granitic slopes. In such slopes, surcharge from the weight of trees would have at best a beneficial influence and at worst a negligible effect as critical, saturated conditions develop in the soil.

MANAGEMENT IMPLICATIONS

Measures to Minimize Mass Erosion Hazard

LOCATION AND SIZE OF CLEARCUT AREAS

The preceding analyses and findings indicate that many slopes in the Idaho batholith are in a state of marginal or metastable equilibrium. Such slopes are vulnerable to both surficial and mass erosion when vegetation is removed by clearcutting or by wildfire. In many instances, road construction associated with timber harvesting appears to have a greater impact than vegetation removal alone (fig. 3). On the other hand, both may have synergistic and cumulative impacts on stability that are hard to distinguish and separate. The slope failures observed in the slope above the road cut in Watershed No. 1 (figs. 10 and 11) are a case in point. The failures appear to be associated with the road cut, but may have been caused in part by wetter conditions in the slope above and by loss of some root cohesion as a result of vegetation removal.

It is not possible at this point to formulate precise rules for location and size of clearcuts to minimize mass erosion hazards. The following guidelines are suggested instead:

1. Limit size of clearcut units;
2. Stagger location of clearcut units or blocks both in space and in time;
3. Leave buffer zone of trees above and below haul roads;
4. Leave buffer zone of undisturbed vegetation along all streams.

SELECTION LOGGING VERSUS CLEARCUTTING

The analyses and findings reported here clearly recommend leaving as much residual timber stand as possible from the point of view of preventing surficial and mass erosion. The greater the amount of standing timber, the smaller the amount of soil root cohesion loss, the smaller the rise in piezometric levels in a slope, and the greater the amount of effective buttressing and soil arching action by residual vegetation. All these beneficial influences are favored by a selection logging system as opposed to clearcutting.

SITE PREPARATION AND ABANDONMENT PROCEDURES

There are a number of measures that are routinely employed in conjunction with timber harvest operations to minimize slope stability problems. These measures are usually specified in various State and Federal forest practice rules. They include such procedures as the seeding and scarifying of roadbeds, removal of temporary road fills, construction of waterbreaks, disposal of slash, and establishment of "vegetation leave areas."

The concept of vegetation leave areas is of particular concern and interest in view of the findings reported here. Trees and woody vegetation should be left undisturbed in critical areas such as steep, slide-prone slopes. Vegetation should also be left intact as much as possible along the margins of haul roads and streams. Gonsior and Gardner's (1971) recommendation bears repeating in this regard, namely, that barriers of live trees should remain undisturbed immediately below the toe of fill slopes and above cut slopes. This recommendation should be weighed, however, against the likelihood of trees falling across roads, owing to possibility of greater vulnerability to root damage and windthrow after right-of-way-clearing.

Hydraulic structures should be constructed with regard to residual areas of slope vegetation. Crossroad drains and waterbars should drain water onto undisturbed vegetation, not over a fill slope or into another road or skid trail. Undisturbed vegetation should be left to provide water spreading areas large enough to accommodate all water draining from roads, skid trails, and similar locations. Particular care should be taken to avoid "stream piracy" during water spreading operations. This can easily happen when water is intercepted by the roadcut in one or more microwatersheds and is carried downslope along the road in the road drainage system and allowed to spread in an adjacent microwatershed.

General Slope Hazard Rating Scheme

The recommendation to leave vegetation intact and in-place in critical areas during timber harvest operations requires that some procedure be employed to identify slopes prone to high mass erosion hazard. Several schemes have been devised for identifying hazardous slopes (Radbruch-Hall 1976; Ward 1976; and Simons and others[2]). Most of these methods consist of mapping information on slope gradient, soil type, geology, hydrology, and past landslide occurrence. This information is integrated by linear combination or factor overlay techniques (Hopkins 1977) to produce a composite map of relative slope hazard.

An alternative approach is to base slope hazard ratings on a geotechnical model employing principles of limiting equilibrium. Geotechnical models such as the infinite slope analysis used here (equation 2) explicitly account for the primary factors in landslide occurrence such as soil strength, ground water influences, vegetative effects, and slope inclination. Geotechnical models represent actual field conditions; hence, they can be used to analyze the response of a hill slope to temporally and spatially varying factors. The geotechnical models or slope stability analyses are routinely used by engineers to evaluate the stability of a particular hillslope, determine the influence of a particular slope modification, and to assess the effectiveness of a particular slope protection measure.

One of the main difficulties with geotechnical models for slope hazard analysis is that they are deterministic. As such they do not satisfactorily take into account uncertainity and variability in the input parameters. A way around this dilemma has been developed by Wu (1976), Ward (1976), and Simons and others[2] by casting the stability equation or factor of safety equation in a probabilistic framework. Instead of computing a single valued safety factor for a slope, one computes a probability of failure. Calculated probabilities can then be grouped into three hazard classes as suggested by Simons and others[2], namely:

1. High probability when $P[F \leq 1] > 60$ percent;
2. Medium probability when $30 \leq P\,[F \leq 1] \leq 60$ percent;
3. Low probability when $P\,[F \leq 1] < 30$ percent.

where $P\,[F \leq 1]$ is the cumulative probability that the safety factor (F) is less than or equal to one.

Computation of the probability of failure requires knowledge of the mean and variance of input variables in the safety factor equation. This type of information is seldom available without extensive testing. This difficulty can be overcome by assuming that the input variables are uniformly distributed, random variables. With this assumption the mean of a random variable is simply found as

$$\bar{X} = \frac{X_a + X_b}{2}$$

and the variance as

$$\mathrm{Var}\,[X] = \frac{(X_b - X_a)^2}{12}$$

where X_a and X_b are the lower and upper limits on the variable X. Thus, probability of failure can be estimated solely from knowledge of the range in each variable, information which is readily available. Simons and others[2] show that the assumption of a uniform distribution provides a conservative estimate of probability of failure. The authors also provide a well-documented example or application of their method for identifying potential landslide areas in terms of their probability of failure.

CONCLUSIONS

The following main conclusions can be drawn from the results of the Pine Creek study in particular and about the role of forest vegetation on stability of slopes in the Idaho batholith in general:

1. Soils that develop on granitic rocks of the batholith are typically shallow, coarse-textured soils (loamy sands to sandy loams) that are found on steep slopes that average 60 percent or more in many drainages.
2. Batholith soils tend to be highly erodible and prone to mass soil movement particularly when disturbed by road construction and timber harvesting.
3. Forest vegetation on the batholith helps to maintain more secure slopes by a series of stabilizing mechanisms. These include mechanical reinforcement by root systems; soil moisture depletion by interception, transpiration, and regulation of snow accumulation and melting; and by buttressing and soil arching action behind embedded tree trunks.
4. Removal of forest vegetation without regard to slope stability can result in loss of the stabilizing influences of forest vegetation. Results of the Pine Creek study show that vegetation often provides the margin of safety between a secure and failed slope.
5. The factor of safety against sliding in slopes of the batholith is very sensitive to cohesion. Almost all, or at least a significant fraction of this cohesion, can be provided by root reinforcement in batholith soils.
6. Several measures are recommended to mitigate the impact of vegetation removal on slope stability. These measures include selection logging in preference to clearcutting, limitation of size of clearcut units, establishment of vegetation leave areas in critical areas, and careful integration of diversions and drainage measures with vegetation leave areas.
7. Live barriers of trees should be left when reasonably feasible below the toe of fill slopes and above cut slopes. Buffer zones of vegetation should also be left along the margin of streams.
8. Critical areas or slopes of high landslide potential can be identified by calculating a probability of failure that takes into account the uncertainty and variability in the input variables in a geotechnical model on which the assessment is based.

PUBLICATIONS CITED

Anderson, H. W.
1954. Suspended sediment discharge as related to streamflow, topography, soil and use. Am. Geophys. Union Trans. 35:268-281.

André, J. E., and H. W. Anderson.
1961. Variation of soil erodibility with geology, geographic zone, elevation and vegetation type in northern California wildlands. J. Geophys. Res. 66:3351-3358.

Bethlahmy, N.
1962. First year effects of timber removal on soil moisture. Intl. Assoc. Sci. Hydrol. Bull. 7(2):34-38.

Bishop, D. M., and M. E. Stevens.
1964. Landslides on logged areas in southeast Alaska. USDA For. Serv. Res. Pap. NOR-1, 18 p.

Brenner, R. P.
1973. A hydrological model study of a forested and a cutover slope. Bull. Hydrol. Sci. 18(26):125-143.

Brown, C. B., and M. S. Sheu.
1975. Effects of deforestation on slope. J. Geotech. Eng. Div., ASCE 101:147-165.

Burroughs, E. R., and B. R. Thomas.
1977. Declining root strength in Douglas-fir after felling as a factor in slope stability. USDA For. Serv. Res. Pap. INT-190, 27 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Clayton, J. L., and J. F. Arnold.
1972. Practical grain size, fracturing density, and weathering classification of intrusive rocks of the Idaho batholith. USDA For. Serv. Res. Pap. INT-237, 35 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Clayton, James L., Walter F. Megahan, and Delon Hampton.
1979. Soil and bedrock properties: weathering and alteration products and processes in the Idaho batholith. USDA For. Serv. Res. Pap. INT-237, 35 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Croft, A. R., and J. A. Adams.
1950. Landslides and sedimentation in the North Fork of Ogden River, May 1949. USDA For. Serv. Res. Pap. INT-21, 4 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Curtis, J. D.
1964. Roots of a ponderosa pine. USDA For. Serv. Res. Pap. INT-9, 10 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Durgin, P. B.
1977. Landslides and the weathering of granitic rocks. Geol. Soc. Am. Rev. Eng. Geol. 3:127-131.

Endo, Taizo, and Takeo Tsuruta.
1969. The effect of the tree's roots upon the shear strength of soil. 1968 Annu. Rep. Hokkaido Branch, For. Exp. Stn., No. 18, p. 167-182.

Gonsior, M. J., and R. B. Gardner.
1971. Investigation of slope failures in the Idaho batholith. USDA For. Serv. Res. Pap. INT-97, 34 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Gray, D. H.
1970. Effects of forest clear cutting on the stability of natural slopes. Assoc. Eng. Geol. Bull. 7:45-67.

Gray, D. H.
1978. Role of woody vegetation in reinforcing soils and stabilizing slopes. *In* Proc., Soil reinf. stab. tech. eng. pract., NSW Inst. Tech., Sydney, Austrialia, p. 253-306.

Gray, D. H., and R. P. Brenner.
1970. The hydrology and stability of cutover slopes. *In* Proc., Interdisciplinary aspects watershed manage., ASCE, p. 295-326.

Hallin, William E.
1967. Soil-moisture and temperature trends in cutover and adjacent old-growth Douglas-fir timber. USDA For. Serv. Res. Note PNW-56, 11 p. Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.

Handy, R. L., and N. S. Fox.
1967. A soil bore-hole direct-shear test device. Highw. Res. News 27:42-51.

Hartsog, W. S., and G. L. Martin.
1974. Failure conditions in infinite slopes and resulting soil pressures. USDA For. Serv. Res. Pap. INT-49, 32 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Hopkins, L. D.
1977. Methods for generating land suitability maps: a comparative evaluation. Am. Inst. Plann. J., 43:386-400.

Jones, F. O.
1973. Landslides of Rio de Janeiro and the Serra das Araras escarpment, Brazil. U.S. Geol. Surv. Prof. Pap. 697, 42 p.
Kitamura, Y., and S. Namba.
1966. A field experiment on the uprooting resistance of tree roots. *In* Proc. 77th Meet. Jap. For. Soc., p. 568-590.
Kozlowski, T.T.
1971. Growth and development of trees, vol. 2. Academic Press, New York.
Lumb, P.
1962. The properties of decomposed granite. Geotechnique 12:226-243.
McMinn, R. G.
1963. Characteristics of Douglas-fir root systems. Can. J. Bot. 41:105-122.
Megahan, W. F.
1972. Subsurface flow interception by a logging road in mountains of central Idaho. *In* Proc., Natl. symp. watersheds in transition. Am. Water Resour. Assoc., Proc. Ser. No. 14, p. 321-329.
Megahan, W. F., and W. J. Kidd.
1972. Effect of logging and logging roads on erosion and sediment deposition from steep terrain. J. For. 70:136-141.
Megahan, W. F., and Delbert C. Molitor.
1975. Erosional effects of wildfire and logging in Idaho. Watershed Manage. Symp. ASCE Irrig. Drain. Div., Logan, Utah, August 11-13, 1975.
Megahan, W. F., N. F. Day, and T. M. Bliss.
1978. Landslide occurrence in the western and central Northern Rocky Mountain physiographic province in Idaho. Paper prepared for 5th North Am. For. Soils Conf., Colo. State Univ., Fort Collins. p. 116-139.
Nelson, D. O.
1976. Soil survey of Middle Fork Payette River area, Idaho. USDA For. Serv. and Soil Cons. Serv., Natl. Coop. Soil Surv. Rep., 55 p.
O'Loughlin, C. L.
1974. The effects of timber removal on the stability of forest soils. J. Hydrol., New Zealand 13:121-134.
Prellwitz, R. W.
1975. Simplified slope design for low standard roads in mountainous regions. NRC-TRB Spec. Rep. No. 160, p. 65-74.
Radbruch-Hall, D. H.
1976. Areal slope stability in a part of the Northern Coast Ranges, California. U.S. Geol. Surv. Map I-982.
Rice, R. M., and J. S. Krammes.
1970. Mass-wasting processes in watershed management. *In* Symp. proc., Interdisciplinary aspects watershed manage. [Bozeman, Mont., August 3-6, 1970.] p. 231-259.
Swanson, F. J., and C. T. Dyrness.
1975. Impact of clearcutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon. Geology 3(7):393-396.
Swanston, D. N.
1967. Soil water piezometry in a southeast Alaska landslide area. USDA For. Serv. Res. Note PNW-68, 17 p. Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.
Swanston, D. N.
1974. Slope stability problems associated with timber harvesting in mountainous regions of the western United States. USDA For. Serv. Gen. Tech. Rep. PNW-21, 14 p. Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.
Swanston, D. N., and W. J. Walkotten.
1970. The effectiveness of rooting as a factor in shear strength of karta soils. USDA Prog. Rep. Study No. FS-PNW-1604:26, Portland, Oreg.
Swanston, D. N., and F. J. Swanson.
1976. Timber harvesting, mass erosion and steepland forest geomorphology in the Pacific Northwest. *In* Geomorphology and engineering. p. 199-221. D. R. Coates, ed. Dowden, Hutchinson and Ross, Inc.
USDA Forest Service.
1977. Transportation engineering handbook. USDA For. Serv. Handb. FSH 7709.11, Reg. 1 Suppl. No. 6, 94 p.
Waldron, L. J.
1977. Shear resistance of root-permeated homogeneous and stratified soil. Soil Sci. Soc. Am. J. 41:843-849.
Wang, W. L., and B. C. Yen.
1974. Soil arching in slopes. J. Geotech. Eng. Div., ASCE 100:61-78.
Ward, T. J.
1976. Factor of safety approach to landslide potential delineation. Ph.D. diss. Colo. State Univ., Fort Collins.
Wineland, J. D.
1975. Borehole shear device. *In* Proc. conf. in-situ meas. soil prop. [ASCE, Raleigh, N.C.] 1:511-522.
Wu, T. H.
1976. Investigation of landslides on Prince of Wales Island, Alaska. Geotech. Eng. Rep. No. 5, Dep. Civil Eng., Ohio State Univ., Columbus, 94 p.

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Results of field studies and supporting theoretical analyses show that forest vegetation often provides a significant margin of safety to the stability of slopes in the Idaho batholith. Woody vegetation contributes to the stability of these slopes by root reinforcement, by soil moisture depletion from interception and transpiration, by regulation of snow accumulation and melting, and by soil arching restraint between tree stems. Removal of vegetation by logging or fire can increase landslide risks at many locations.

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The Intermountain Station, headquartered in Ogden, Utah, is one of eight regional experiment stations charged with providing scientific knowledge to help resource managers meet human needs and protect forest and range ecosystems.

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